Austin, James R. (2007) ***The Cloncurry Lineament: a long-lived deep crustal structure that acted as a metasomatic pathway during ca 1530-1500 Cu-Au mineralisation, Mount Isa Inlier, Australia.*** **PhD thesis, James Cook University.**

APPENDICES

Appendix1 - The Cloncurry Lineament 1:50,000 Geological Map

(See back pocket)

The Cloncurry Lineament
1:50,000 Geology
pmd*CRC
part of a PhD Thesis *Crustal Structure Of The Mt Isa Eastern Succession: The Cloncurry Lineament* © 2007 by J. R. Austin
Sediments and Sedimentary Rocks
Quaternary — Qa — Alluvial sand and gravel
Cainozoic — Czs — Alluvial and Colluvial sand, silt, gravel and clay
Late Jurassic-Early Cretaceaous — JKg — Gilbert River Formation: Conglomerate, Coarse-medium sandstone, siltstone and claystone
Meta-sedimentary Rocks
Soldiers Cap Group ~1690-1650 Ma
Pot — Toole Creek Volcanics; Amphibolite: (1658±8 Ma)
Pot — Toole Creek Volcanics; Schist, Quartzite: (1658±8 Ma)
Pon — Mt Norna Quartzite (1654±4)
Pol — Llewellyn Creek Formation (>1686±8; 1666±14 Ma)
Po — Albite-Actinolite Calc-silicates
Po — Undifferentiated Soldiers Cap Group (~1690-1650 Ma)
Doherty Formation 1750-1725 Ma
Pkd — Marble-Marble Breccia
Pkd — Banded Albite-Actinolite Calc-silicates
Pkd — Calc-silicate breccia
Pkd — Laminated-Massive Calc-silicates
Intrusive Rocks
1516-1490 Ma — Pgi — Squirrell Hills Granite
1536-1520 Ma — Pgi — Saxby Granite
Pgi — Mount Angelay Granite
1552-1545 Ma Tonalitic Suite — Pg — Undifferentiated Old Granites
Pgq — Maramungee Granite
Pgq — Boorama Tank Gneiss
Various Ages — di — Dolerite, Meta-dolerite, Amphibolite
Various Ages — peg — Pegmatite
Structure
Basalt Dyke
Dolerite Dyke
Pegmatite Dyke
Granitic Dyke
Mineralisation observed in field
Mineral prospect
Fault / Inferred Fault
Mylonite
Reverse Fault / Thrust
Anticline/antiform
Syncline/synform
Minor anticline/antiform
Minor syncline/synform
Minor anticline/antiform with axial plunge
Minor syncline/synform with axial plunge
Foliation
S2 Foliation
Bedding
Cleavage (S2)
Cleavage (S3)
Mylonite
Jointing
Lens
Vein
Fault (dashed line shows fault orientation)
Clast Alignment in breccia
Dyke
Crenulation (S1\S2)
Stretching Lineation
Aerial photo lineaments
Bedding, 0-45°/ 45-90° (aerial interp)
Mylonitic Fabrics
Lineations
Bedding-Foliation
Faults
Faults
Legend
High Level Magnetic Worm
High Level Gravity Worm
Major Mineral Deposit
Magma Mingling Site
Williams Batholith
Mt Fort Constantine Volcanics
Ernest Henry Diorite
Dolerite Dykes and Sills
Wonga Batholith
Masked areas sit beneath Mesozoic cover
Mount Albert Group
Young Australia Group
Soldiers Cap Group
Doherty Formation
Corella Formation
Ballara-Mitakoodi Quartzite
Marraba Volcanics
Argylla Formation
Kalkadoon/Leichhardt
Basement
Williams River
Saxby Waterholes
Surprise Ck
Doherty Ck
Fullarton
Mount Kalkadoon Cu
Mt Angelay
Mallee Gap
The Three Sisters
Glen Idol
Fairmile prospect Pb-Zn-Cu Ironstone
Landsborough Cu
Louise prospect (Cu)
Boorama Creek
Mt Tracey
Mt Boorama
Dingo prospect Cu-Pb-Zn
Maramungee Creek
Maramungee prospect Pb-Zn-Cu Skarn
McKinlay River
Ding Ding Ck
Aerial photography coverage
Cloncurry
Naraku Granite
ERNEST HENRY
DUGALD RIVER
MARY KATHLEEN
GREAT AUSTRALIA
Seismic Section shown (Fig 4.5a)
Holy Joe Creek Structure
Middle Creek anticline
Snake Creek anticline
Mitakoodi Antiform
Mount Angelay Granite
Saxby Granite
Wimberu Granite
HAMPDEN GROUP
YOUNG AUSTRALIA
MOUNT ELLIOTT
SELWYN
Squirel Hills Granite
CANNINGTON
OSBORNE
TICK HILL
FOUNTAIN RANGE FAULT
PILGRIM
SEISMIC LINE
CLONCURRY WORM
CLONCURRY FAULT
AREA MAPPED IN DETAIL
ELOISE
80 km
MAP MODIFIED FROM NORTHWEST QUEENSLAND MINERAL PROVINCE REPORT, 2000.
Mount Isa Inlier
Mt Isa
Cloncurry
Eastern Succession
QUEENSLAND
Brisbane
0 5 10 15 20
TRANSVERSE MERCATOR PROJECTION AMG ZONE 54 - WGS84   MODIFIED FROM BLAKE ET AL (1983) & DONCHAK ET AL (1984)

Appendix 2 - The 1800–1610 Ma stratigraphic and magmatic history of the Eastern Succession, Mount Isa Inlier, and correlations with adjacent Paleoproterozoic terranes.

Damien R.W. Foster, James R. Austin (30%)

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The 1800–1610 Ma stratigraphic and magmatic history of the Eastern Succession, Mount Isa Inlier, and correlations with adjacent Paleoproterozoic terranes

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Appendix 3 - The crustal scale architecture of the Eastern Succession, Mount Isa: The influence of inversion

T.G. Blenkinsop, C.R. Huddlestone-Holmes, D.R.W. Foster, M.A. Edmiston, P. Lepong, G. Mark, **J.R. Austin** (10%), F.C. Murphy, A. Ford, M.J. Rubenach

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The crustal scale architecture of the Eastern Succession, Mount Isa: The influence of inversion

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Appendix 4: Pre-conference Field Trip Structural and Metasomatic Evolution of the Mt Isa Block 21st – 27th August 2005

M. J. Rubenach, T.G. Blenkinsop and J. R. Austin (10%)

Geological Society of Australia
Specialist Group: Tectonics and
Structural Geology

STOMP Structure, Tectonics and Ore Mineralization Processes

Geological Society of Australia
Specialist Group: Tectonics and Structural Geology

Pre-conference Field Trip
Structural and Metasomatic Evolution of the Mt Isa Block
21st – 27th August 2005

M. J. Rubenach, T.G. Blenkinsop and J. R. Austin

JAMES COOK UNIVERSITY

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CONTENTS

1. INTRODUCTION: GEOLOGICAL HISTORY OF THE MOUNT ISA INLIER

Two major orogenic cycles affected the Mount Isa Inlier (Location map Figure 1). The first was terminated by the Barramundi Orogeny (1840-1890 Ma), which produced metamorphic rocks such as the Yaringa Metamorphics and Kurbayia Migmatite of which only a few remnants are exposed. In the second cycle, which terminated with the Isan Orogeny, deposition took place in a series of probably intracontinental rift basins, probably in a back-arc setting (Blake, 1987; Blake & Stewart, 1992; Giles & Betts, 2002; Betts et al., 2002; Butera, unpub. data). The rocks comprising the rift basins have been grouped into three main cover sequences (Figure 2). Cover sequence 1, mainly volcanics and coeval granites, now occupies a central north-south belt, the Kalkadoon Leichardt Block. During deposition of cover sequences 2 and 3, this block acted as a basement high, with the Western and Eastern Successions deposited on either side (Figures 2, 3). The second tectonic cycle terminated with the Isan Orogeny, ca 1500-1610 Ma, that resulted in multiple deformation/metamorphic events. A-type granites, mainly the Williams and Naraku Batholiths, were emplaced into the Eastern Succession during the later stages of the Isan Orogeny. However, significant local deformation and metamorphism, with associated granite emplacement, also occurred between the deposition of cover sequences 2 and 3 in both the Eastern Succession (the Wonga event and Wonga Batholith) and Western Succession (syn-Sybella event and Sybella Batholith). High-Fe quartz tholeiites were deposited as volcanics or intruded as dolerites or gabbros throughout the history of the Inlier.

The field trip stops are shown on Figure 2. This field trip concentrates on the deformation processes of the Isan Orogeny and the Wonga and syn-Sybella events. Many aspects of the overall tectonic environment remain uncertain, but a model explaining the major events of the Isan Orogeny, namely collision of the Southern Australian Craton followed by collision with North American blocks, is summarised in Figures 4-5.

Some of the key issues that remain to be resolved about the mid-Proterozoic tectonics of the Mt Isa inlier, which are the main themes of the trip and hopefully will form the focus of discussion, are:

- The tectonic settings of sedimentation and deformation,
- The style of contractional deformation tectonics - thin or thick skinned?
- Reasons for the long lived, inferred high geothermal gradients and repeated magmatism
- The driving forces for intracontinental deformation
- The interrelationships between magmatism and deformation

More specific structural features that we will consider include:

- Transitions between magmatic and solid sate deformation
- Outcrop scale relations between metasomatism, metamorphism and deformation
- The internal structure of high-level fault zones, including their permeability
- Mechanisms capable of causing regional scale and localised brecciation
- How complex does a deformation history have to be in a multiply deformed terrain? Is D1 to 3 enough?
- The relationships between deformation, fluid flow and mineralization

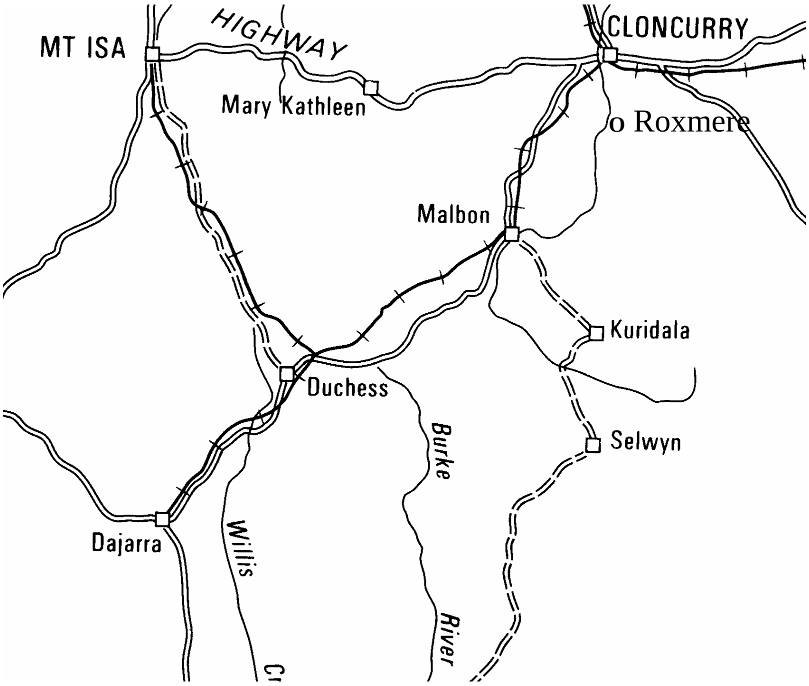

Figure 1. Location map.

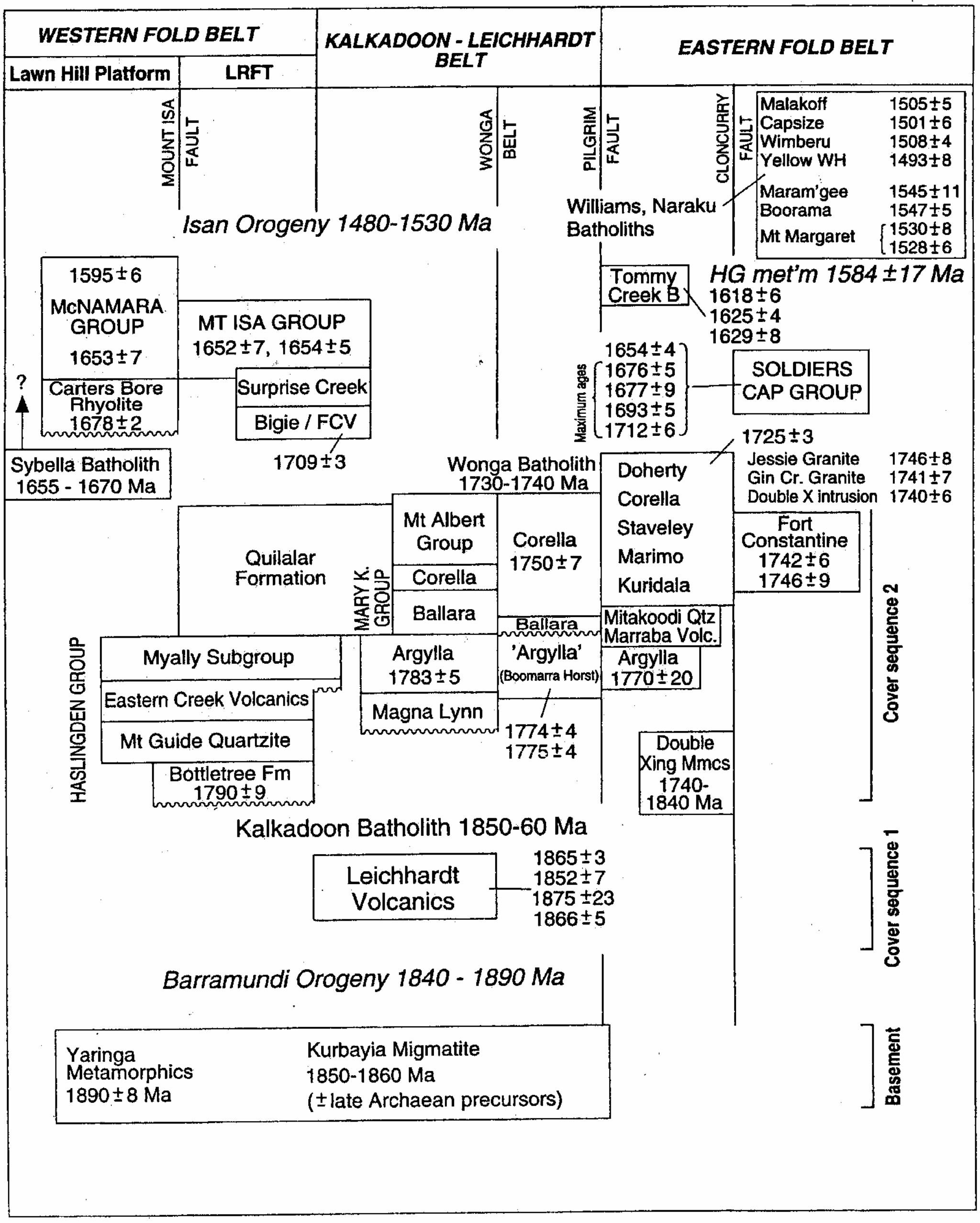

Figure 2. Chronostratigraphic framework for the Mount Isa Inlier, from Page & Sun (1998). Units such as the Soldiers Cap, Mount Isa, and McNamara groups are cover sequence 3. In this field-guide the Isan Orogeny incorporates all events in the range 1500-1610Ma.

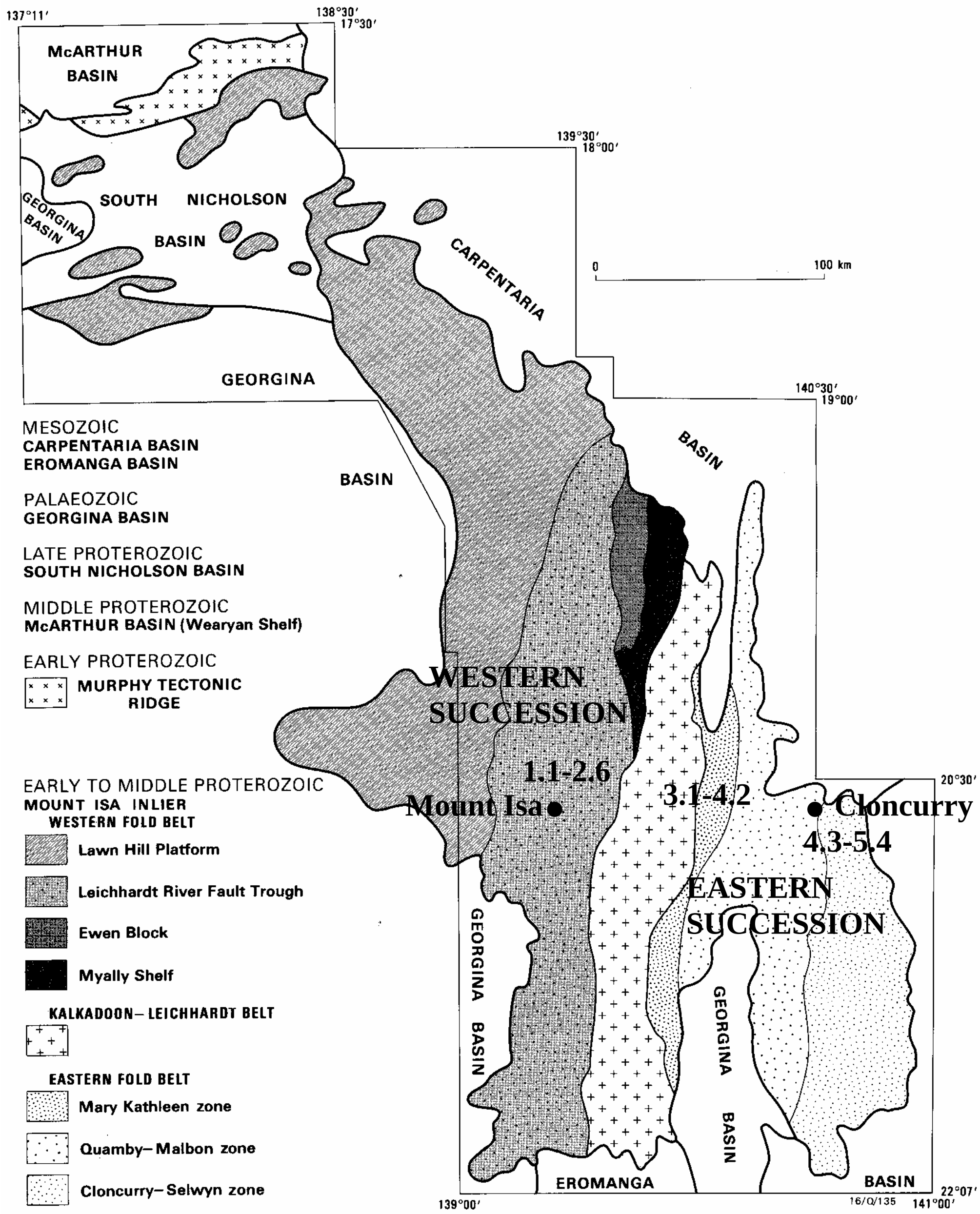

Figure 3. Tectonic subdivisions of the Mount Isa Inlier. Field trip stops are shown.

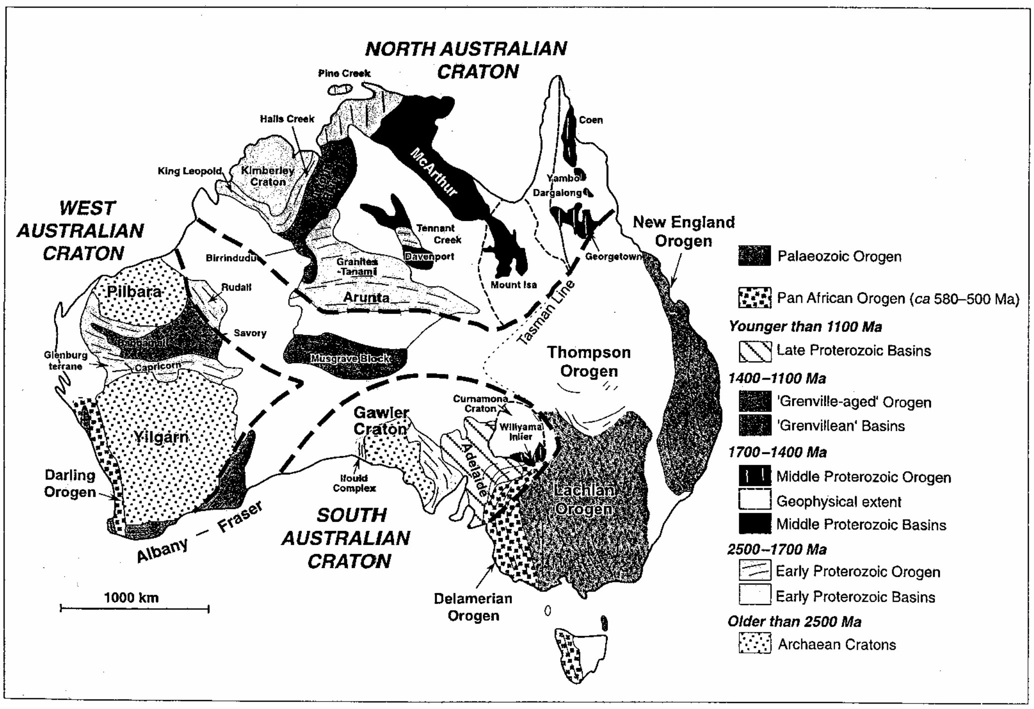

Figure 4. Precambrian cratons, from Betts et al.(2002)

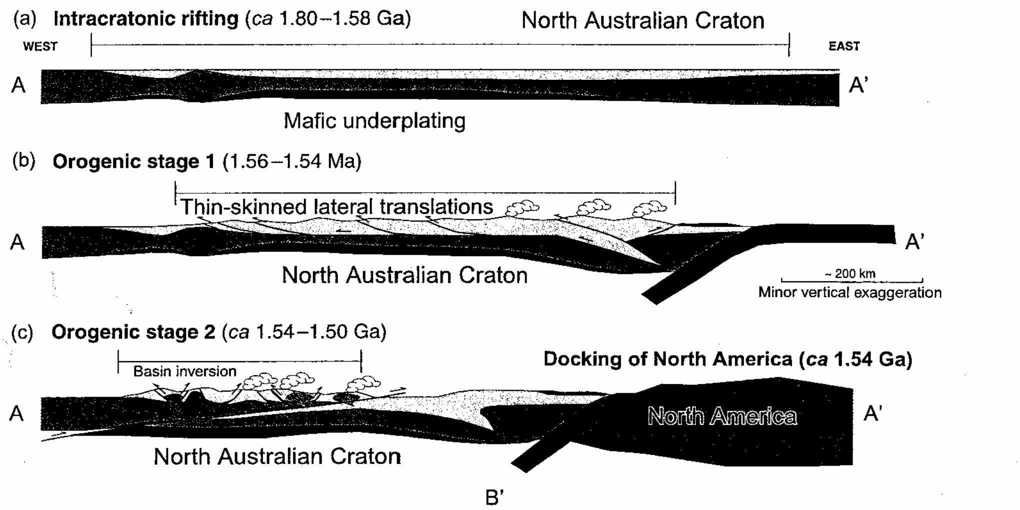

Figure 5. Model proposed by Betts et al. (2002) to explain the Isan Orogeny. The sections are east-west.

2. A NOTE ON STRUCTURAL HISTORY AND CORRELATION

Nomenclature used by geologists in describing the structural history of an area or region generally leads to numerous problems. Such problems in the Mount Isa Inlier are summarized in Figs. 6-8. Complicating factors in determining structural histories and correlating structures between different areas include localization of strain, heterogeneity of strain, diachroneity of events, and reactivation of foliations, along with the problems inherent in most scientific models. As for ductile events this guidebook will refer to the following;

1. Wonga event, 1730-1750 Ma, synchronous with the Wonga Batholith in the Mary Kathleen region. Affects rocks up to cover sequence 2 in the Eastern Succession
2. Syn-Sybella event, ~1672 Ma. Affects the earlier phases of the Sybella Granite and cover sequence 2 rocks adjacent to the batholith.
3. Isan Orogeny, D_1 events. These resulted from essentially NS shortening, and produced recumbent folds, thrusts, shear zones, and EW-trending upright folds. Age not certain.
4. Isan Orogeny, events associated with essentially EW shortening. These include "D_2" and the metamorphic peak (1580-1600 Ma), and a number of subsequent events (e.g., D_3, D_4, etc, continuing to at least 1530 Ma).

D mystifying D formation events

Oliver (1995)		D_1		D_2		D_3						?D_4				
Adshead-Bell (1998)				D_1		D_2			D_3	D_4		D_5	D_6			
Bell & Hickey (1998)				D_1		D_2			$D_{2.5}$	D_3		D_4	D_5			
Bell (1983)				D_1		D_2				D_3						
Loosveld (1989)	D_{e1}	D_{e2}	D_{e3}	D_{c1}		D_{c2}				D_{c3+}						
Mares (1998)				D_1	D_2	D_3		D_4		D_5	D_6	D_7				
DeJong & Williams (1995)			D_{e3}	D_{c1}	D_{c2a}	D_{c2b}				D_{c3}	D_{c3+}					
Holcombe et. al. (1992)		D_1^K		D_2^K		D_3^K										
Lewthwaite (2000)				G_1		G_2	G_3			G_4						

Figure 6. Correlation of deformation events, Mount Isa Inlier.

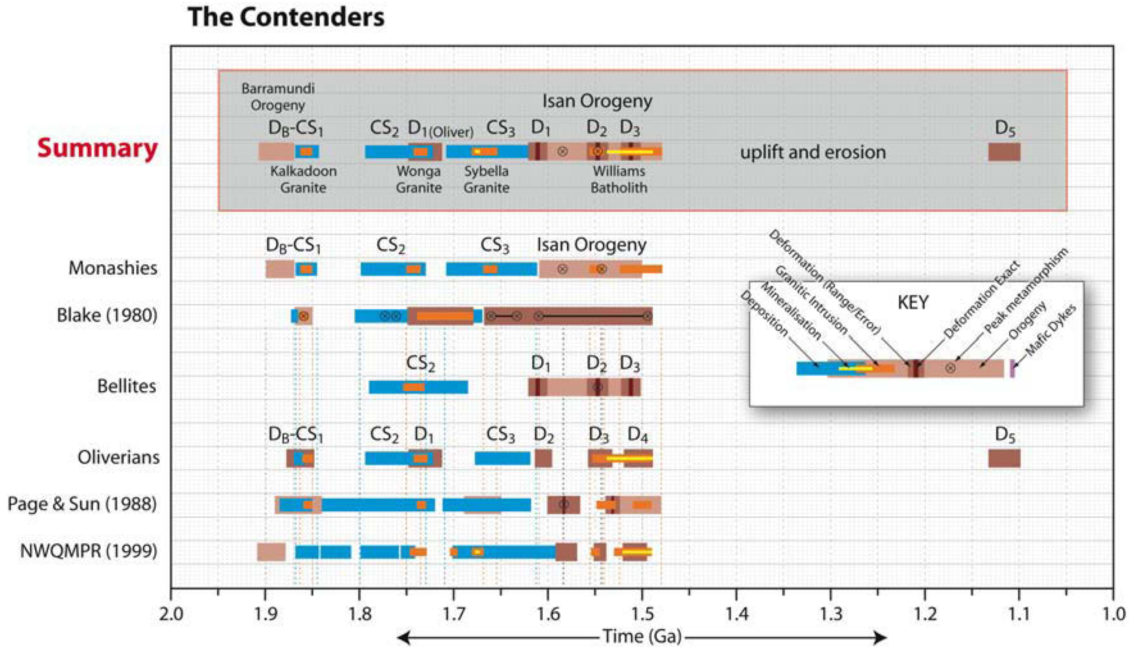

Figure 7. Deformation histories, Mount Isa Inlier.

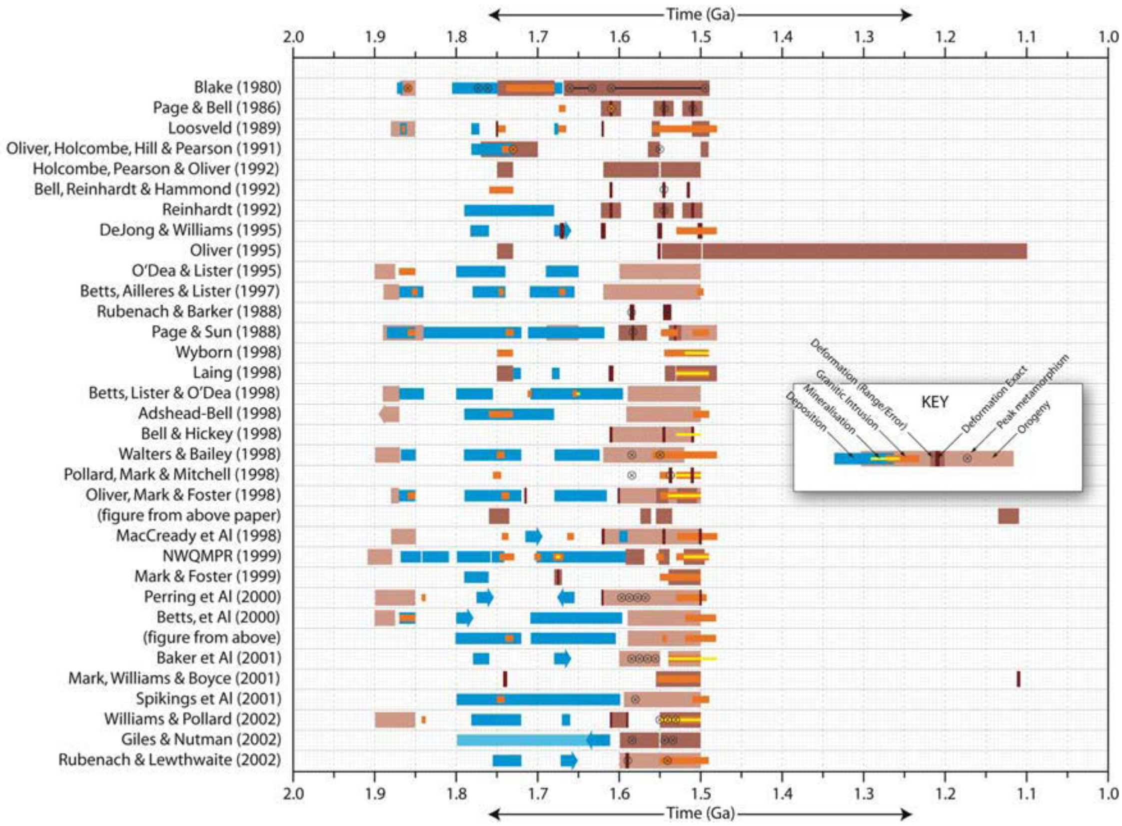

Figure 8. Deposition and orogenic histories, Mount Isa Inlier.

3. A NOTE ON THE METAMORPHISM.

Figure 9 shows the isograds in the inlier. They generally relate to the peak of metamorphism in the Isan Orogeny. The isograds are based on porphyroblasts in pelitic rocks, or rock-buffered calcsilicate assemblages in the absence of pelites. I(n the absence of suitable pelitic or calcsilicate assemblages, temperatures and pressures for the Kalkadoon-Leichardt Block have been determined from new amphibole geothermobarometers by Foster (2003). The diopside zone in rock buffered calcsilicate rocks approximately corresponds with the sillimanite isograd (~590°C).

Note that amphibolite facies rocks are concentrated in relatively narrow NS belts, a belt through Mount Isa, the Kalkadoon-Leichardt Block, the Wonga Belt and the Cloncurry-Osborne Belt. The highest grade rocks are upper amphibolite facies (around 700°C), and occur in the Cannington and Osborne areas at the southeast extremity of the inlier, and the May Downs Gneiss west of Mount Isa (e.g., Kim & Bell, in press).

The metamorphism is dominantly low-P/high-T, with anticlockwise P-T-t paths proposed for the Mount Isa and Mary Kathleen areas (Rubenach, 1992; Reinhardt, 1992). The paths for the Snake Creek anticline are more complex (see day 5). To generate the required temperatures in the middle crust is difficult, with magmatic heating and self-heating due to elevated contents of heat forming radioactive elements (mainly K, U and Th) in the metasedimentary rocks or adjacent older granites being the most commonly proposed models. Note that granites occur in all the amphibolite facies belts, but, with the exception of abundant pegmatites and migmatites in the highest grade rocks, no moderate to large bodies of granite intruded at the regional metamorphism peak in the Isan Orogeny. Self heating from the Sybella Granite could explain the Isan Orogeny metamorphism west of Mount Isa (McLaren et al., 1999), but such a model cannot account for metamorphism at a similar age in the other belts in the inlier. However, self heating no doubt makes a contribution to the overall thermal budget.

The problem with the magmatic heating model is that the larger granites are the wrong ages and the migmatites are really an effect rather than the cause of the thermal anomalies. At least some mafic rocks intruded around the metamorphic peak (see day 5), but these appear to be volumetrically too small. However, mafic rocks were emplaced throughout the tectonic history of the inlier (e.g., Blake, 1987; Ellis & Wyborn, 1984). Modelling of the crystallization of these predominantly high-Fe tholeiites suggests significant fractionation in large lower crustal magma chambers. It is suggested that heat from such mafic underplating was advectively transferred to the middle crust by granite melts, by the pegmatites and migmatites during periods of higher strain around the metamorphic peak, and by larger bodies of granite during periods of lower strain.

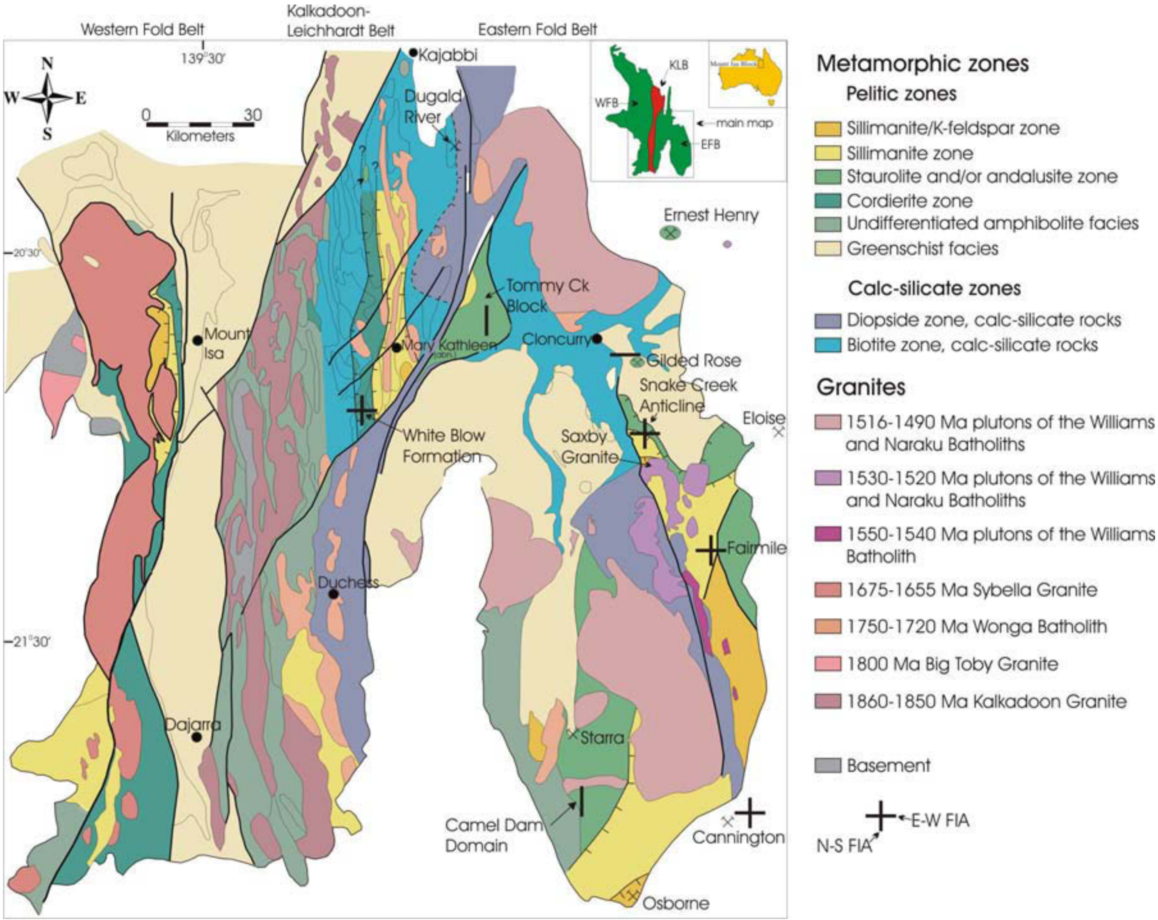

Figure 9. Isograd modified from Foster (2003). Locations of EW and NS FIA's (foliation intersection axes in porphyroblasts) are from Sayab (2005).

DAY 1 (SUNDAY AUG. 21). MOUNT ISA – FAULTS AND STRUCTURAL CONTROL OF METASOMATIC ROCKS

Stop 1.1. Road cuttings at the start of the road to May Downs Station, northern outskirts of Mount Isa
The cuttings show west-dipping weathered Magazine Shale, the host unit of the Mount Isa ore deposits. A weak S_2 cleavage is present, along with an open F_4 fold.

Stop 1.2. Paroo, Mount Isa and Holly Faults. 1.5 km on May Downs road.
The traverse will commence on an outcrop of Magazine Shale in a creek bed, northern side of the road. The shales show a strong cleavage indicating antiform east. The Paroo Fault, where Eastern Creek Volcanics have been thrust over Mount Isa Group (Bell, 1991; see Fig.), is not exposed along the creek, but greenstone outcrops occur within 100m to the north. The Mount Isa Fault, less than 20m west of the Paroo Fault, is marked by a quartz blow in the creek near the road. This Fault dips steeply to the west and has a reverse movement of up to 6 km (west side up) (Bell, 1991). Matthai et al. (2004) presented a model for the origin of the Mount Isa copper deposit involving forced fluid convection driven by progressive displacement on the Mount Isa Fault. However, there is no evidence for the 200°C offset in metamorphic grade required by their model. West of the Mount Isa Fault is a sequence of strongly foliated biotite-grade quartzites and quartz-rich schists that are either basal Mount Isa Group or Lena Quartzite (Eastern Creek Volcanics). These are west dipping and overturned, as evidenced by cross bedding in an outcrop that we will examine in the creek. 120 m west of the Mount Isa Fault is the Holly Fault, a steep fault with west side down. We will examine M/W upright folds in the Bortala Formation (Myally Subgroup) in the creek west of the Holly Fault. The Bortala Formation typically consists of schists and metapammites comprised of quartz, green muscovite, high-Mg chlorite and biotite, epidote, feldspars and haematite (green red-beds). It also contains scattered lenses of marble and metasomatic massive tremolite and plagioclase tremolite pods (Huang & Rubenach, 1995). Along a creek on the north side of the road we will examine tremolite pods, and folded beds showing spectacular ripples. Assemblages indicate greenschist facies metamorphism at about 450ºC.

Stop 1.3. Meernurker Fault, chlorite-quartz alteration, and plagioclase-tremolite pods.
Take the right fork in the road at the western end of stop 1.2, passing the molanite plant after a few hundred metres, then proceeding another 1.4 km north of the road to a prominent knoll with a quartz vein a hundred metres east of the road.
We will examine the Meernurker (Tailings Dam) Fault about 100 m west of the road. Shallowly dipping metapsammitic rocks of the Bortala Formation are in contact with a wide zone of chlorite-quartz rocks, formed by metasomatism of basalts of the Eastern Creek Volcanics. Clasts of quartzites in the schists at the contact are interpreted as fault breccia (Bell, 1991). The fault is interpreted in terms of a lateral ramp to a south-directed thrust duplex complex to the east (Bell, 1991; see Figures.). In a detailed study of the structure along the Molanite Valley, Huang (1993) found no evidence for or against this view. Regardless of its earlier history the fault must have a post-D_2 movement, as

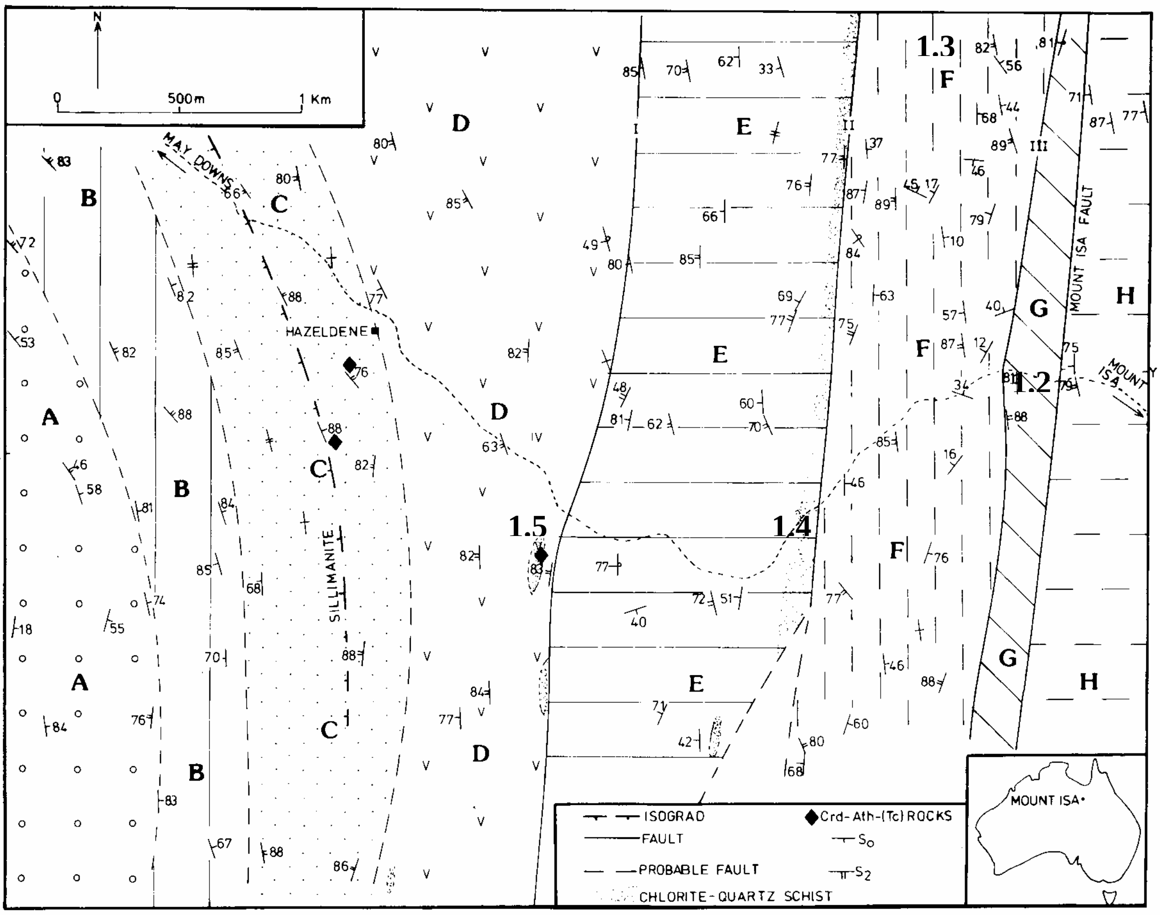

Figure 10. Map of the "Hazeldene" area, just NW of Mount Isa, from Rubenach (1992). Field trip stops 1.2-1.5 are shown. Units are as follows: A, May Downs Gneiss; B, Mount Guide Quartzite; C, Eastern Creek Volcanics, schist-rich zone; D, Eastern Creek Volcanics, metabasalt-rich zone; E, Eastern Creek Volcanics, Lena Quartzite; F, Myally Subgroup, mainly Bortala Formation; G, ? Lena Quartzite or basal Mount Isa Group; H, upper Mount Isa Group

cordierite schists just west of the fault indicate a temperature of at least 550ºC, compared with 450ºC for the Bortala Formation.

Over to the knoll to the east of the road, a plagioclase-tremolite rock is centred around a quartz lens which probably infills the main fracture feeding the external fluids. Note the sharp metasomatic front and the slight deflection of S_2 around the pod (Fig.). The abundant plagioclase-tremolite and tremolite pods in the Bortala Formation, Molanite Valley, are interpreted by Huang & Rubenach (1995) to have formed late in D_2.

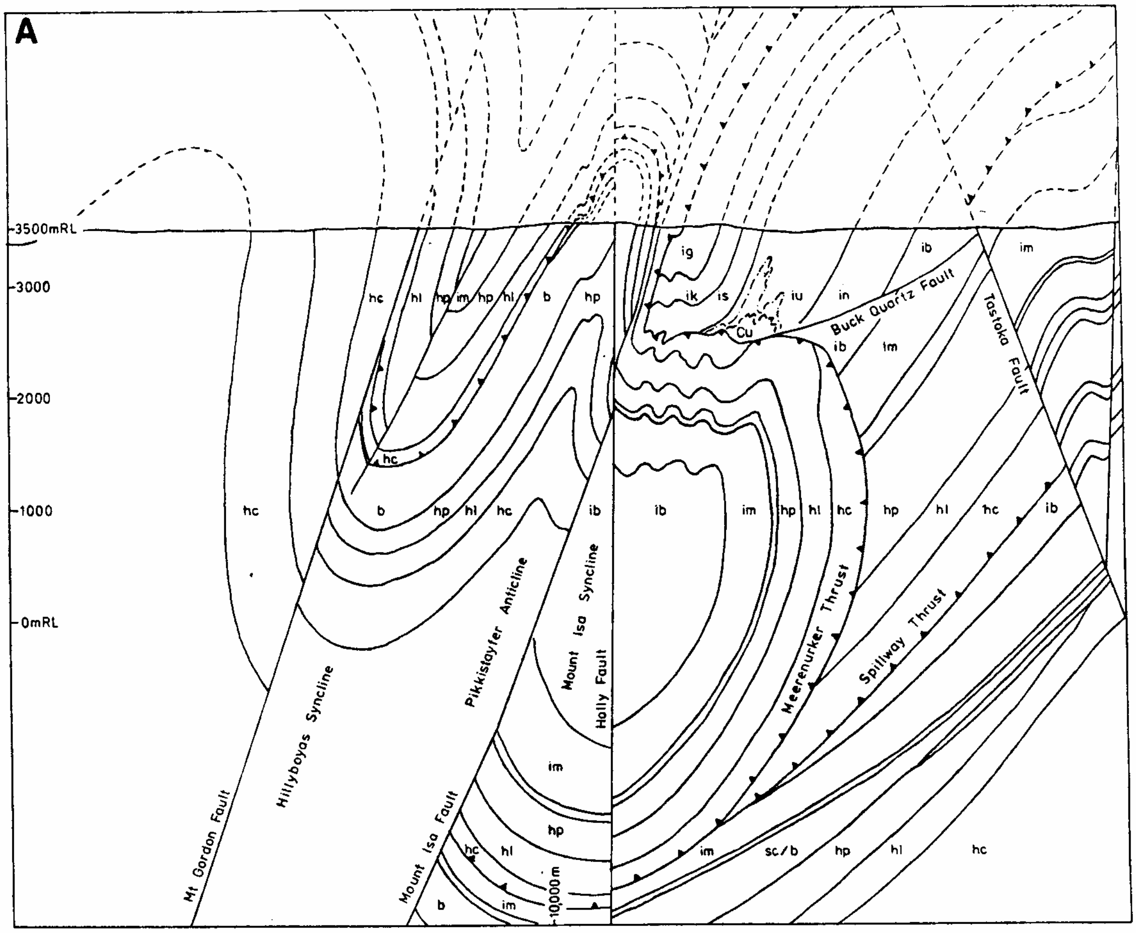

FIG. 17. A.-D. Series of west-east cross sections interpreted from surface structural relationships through the Mount Isa mine (A, 34,500 m N), the Crystallena block (B, 28,000 m N), the Native Bee area south of the Crystallena block (C, 23,800 m N), and Copalot, 17 km south of Mount Isa (D, 20,100 m N). The location of these sections is shown in Figure 2. Note the relative movements on the Mount Gordon, Holly, Mount Isa, and Tastoka faults. Note the geometry of the Meerenurker thrust as it cuts downward on the lateral ramp across Mount Isa and Haslingden Group rocks in the Spillway thrust sheet through to the Moondarra Siltstone in the Mount Isa thrust sheet. Note the change in location of the Mount Gordon fault relative to the Hillyboyas syncline and the consequent change in distribution of rocks uplifted to the west against those to the east from section to section. Note the change in rock distribution across the Tastoka fault from section to section and how this fault provides many solutions to puzzling features of the geology of the Mount Isa Valley. Abbreviations: Prefix h = Haslingden Group rocks, prefix i = Mount Isa Group rocks; b = Bortala Formation, gs = Sybella Granite, hc = Cromwell Metabasalt, hg = Mount Guide Quartzite, hl = Leander Quartzite, hp = Pickwick Metabasalt, ib = Breakaway Shale, ig = Magazine Siltstone, ik = Kennedy Siltstone, im = Moondarra Siltstone, in = Native Bee Siltstone, is = Spear Siltstone, iu = Urquhart Shale, sc = Surprise Creek Formation, wp = Warrina Park Quartzite.

Figure 11. E-W cross-section through the Mount Isa Mine, from Bell (1987, Fig 17. A-D).

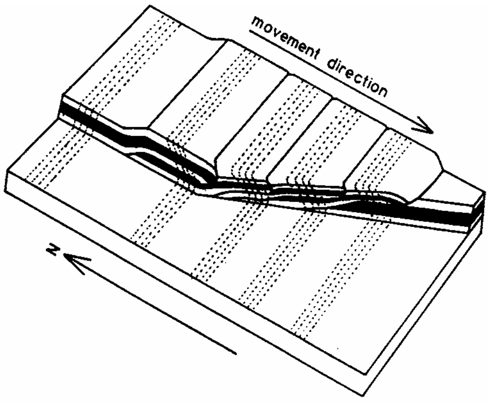

Figure 12. Lateral ramp model of Bell (1987).

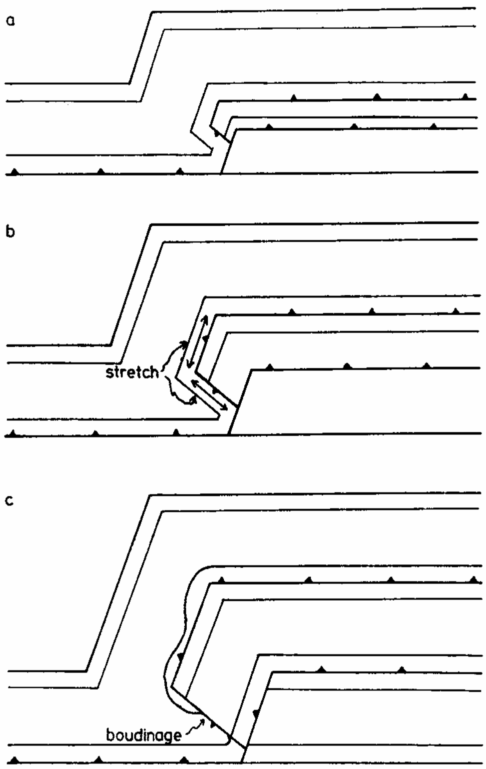

Figure 13. Cross sections showing progressive development of lateral ramp, from Bell (1987).

Stop 1.4. Mount Gordon Fault and metasomatic chlorite-quartz-(anthophyllite-talc) rocks.

We will return to the May Downs road, drive about 800 m SW, turning a few hundred metres down a road to the south near a cattle grid to a gate. We will walk a few hundred metres SSE to the Mount Gordon Fault, which juxtaposes quartzites to the east against amphibolites and metasomatized equivalents (both are units of the Eastern Creek Volcanics). Bell (1991) interprets the Mount Gordon Fault as a steep reverse fault with around 4 km west side up. Near the fault foliated amygdaloidal metabasalts (amphibolites) contain zones of chlorite-quartz schists, with small anthophyllite needles locally present. Patches of epidozites are rare.

The alteration of metabasaltic rocks of the Eastern Creek Volcanics to chlorite-quartz rocks is very common, particularly adjacent to NS faults. Locally the schists contain cummingtonite or anthophyllite, and more rarely talc. They did not form as retrograde shear zones, as the growth of amphiboles, and especially their conversion around the sillimanite isograd to cordierite anthophyllite rocks testify (see stop 1.5). Alteration of basalts to the chemical equivalents of the chlorite-quartz rocks is well known from ocean floor basalts where sea-water circulation around mid-ocean ridges has stripped Ca and Na from the rocks. At higher temperatures Mg and Na are removed to form epidozites. The tectonic environment for the Eastern Creek Volcanics is one of intracontinental rifting rather than mid-ocean ridge, but the principal is the same. The concentration of the alteration along faults is significant; either the faults were initially active during deposition, or saline fluids circulated when the faults were active in a later event, for example during the formation of the Mount Gordon Arch in the syn-Sybella event (see discussion Stop 2.2).

The timing of the alteration in the Eastern Creek Volcanics is important regarding the sources of fluids involved in the formation of the Mount Isa copper orebody. As a number of publications emphasize dissolution of Cu during alteration of the Eastern Creek volcanics to chlorite or epidote-bearing assemblages (e.g., Hannan et al., 1993; Heinrich et al., 1995). However, it is clear that the alteration west of the Mount Isa Fault was pre-D_2, and not syn-D_4, believed to be the timing of the Cu mineralization (NB, this event is generally called D_3; Bell & Hickey refer to the intervening event forming shallowly-dipping axial plane structures as $D_{2.5}$).

Stop 1.5. Structural controls for cordierite metasomatic rocks, P-T-t path, problems concerning pegmatites and D_2 age.

From the track intersection near Stop 1.4 we will drive about 1.5 km west along the May Downs road to a former homestead area (near a Telstra dish). We will examine a few F_2 folds of variable plunge. Cordierite is common in schists, and has been interpreted as growing early in D_2 (Rubenach, 1992). Unusual metasomatic rocks consisting of cordierite + quartz (± andalusite ± albite) have replaced muscovite schists adjacent to boudins of amphibolitized metadolerite (Figure 14). It is proposed that microfracturing associated with boudinage allowed infiltration of Mg-rich fluids. Marginal to local small retrograde chlorite shear zones andalusite and cordierite in the metasomatic rocks have been replaced by chlorite + kyanite. Combined with the prograde replacement of cordierite just west of this locality by andalusite and sillimanite this implies an anticlockwise P-T-t path (Rubenach, 1992).

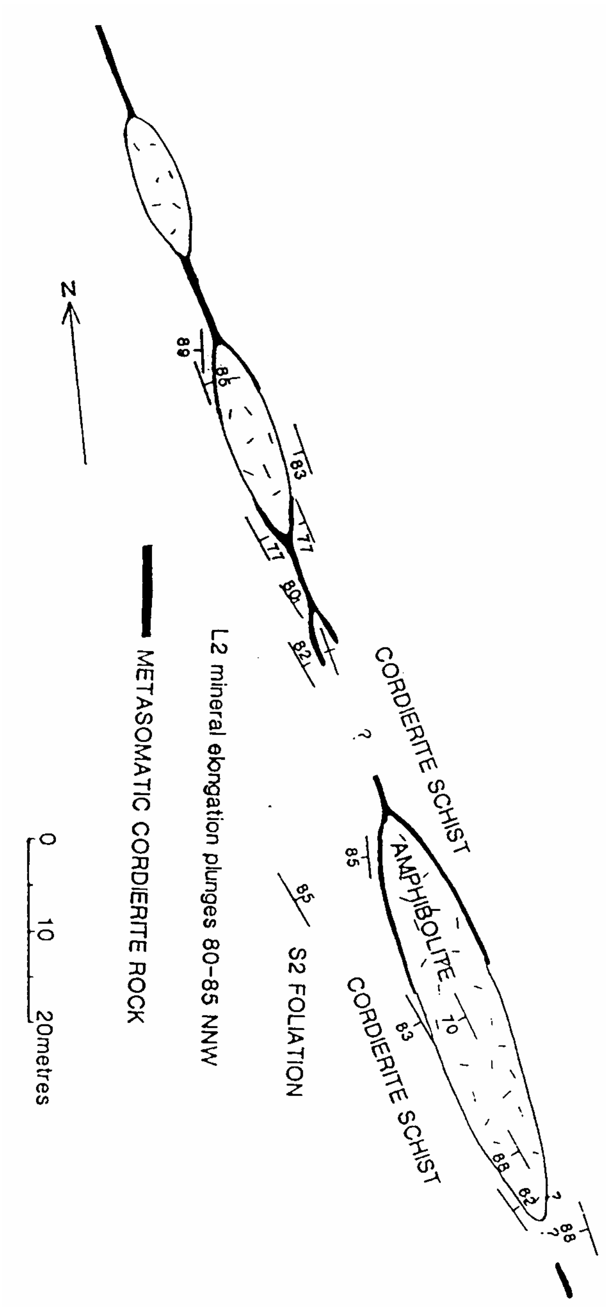

Figure 14 . Map of some amphibolitized metadolerite boudins with partly enclosing metasomatic cordierite rich rocks, within muscovite-cordierite schists, Stop 1.5

We will also examine bodies of Mica Creek Pegmatites and tourmalinization of schists adjacent to pegmatites and some quartz lenses. These have been dated (U-Pb using SHRIMP) by Connor and Page (19) at 1532 and 1492 Ma. The older ones were thought to be synchronous with D_2 (and therefore the metamorphic peak) on the basis of alignment of tourmaline in L_2 and other structural observations. However, Hand and Rubato (2002) dated monazite from a cordierite-anthophyllite rock a few hundred metres to the south, obtaining an age of 1575 Ma, more in line with D_2 ages across the Inlier (e.g., Hand & Rubatto, 2002; Giles & Nutman, 2003). We will visit the cordierite-anthophyllite rock, situated a few hundred metres SSW of the pegmatites. It is separated from adjacent muscovite-cordierite schists by a metasomatic cordierite-quartz rock. The conclusion that the latter replaced muscovite schists whereas the cordierite-anthophyllite rock was formed by metasomatism and subsequent metamorphism of a basaltic rock is confirmed by geochemistry. It is suggested that during conversion of chlorite-quartz rocks to cordierite-anthophyllite rocks (at around 600°C, 4 kbar), fluids rich in Mg but poor in K derived from the latter produced the cordierite quartz rocks adjacent to boudinaged metadolerites.

DAY 2. SYBELLA BATHOLITH AND SYBELLA EVENT.

Stop 2.1. Granite contact, May Downs Road, 3.6 km from Sandy Creek crossing.
Figure 15 is a map of the northern part of the Sybella Batholith, while Figure 16 is a revised history of basin development in the Western Succession. At stop 2.1, about 20 m from the road, the contact of the Sybella Granite and amphibolite of the Eastern Creek Volcanics is sill-like, dipping to the SW. Several thin sheets of granite are parallel to the main contact. Cross-bedding in nearby quartzites indicates the contact is overturned, interpreted by Bell & Hickey (1998) to be the result of D_3 deformation. Xenoliths of amphibolite near the contact indicate a deformation event prior to the emplacement of this phase of the granite ("syn-Sybella event" – see next few stops).

Stop 2.2, Mosses Dam track on Kitty Plain.
About 3 km further west along the May Downs road is track. About 3km along this road (through a locked gate) is a hill of granite west of the road. We will walk east for several hundreds of metres. Lithologies here include medium to coarse porphyritic granite (Main Phase, Sybella Granite), dolerite, extensive mixed and mingled rocks, hybrids and a slightly younger felsic microgranite (Figs). The mixed rocks exhibit both magmatic flow and tectonic fabrics. The microgranite, dated here at 1683±3 Ma, truncates the strong fabrics. The Main Phase Granite has been dated at 1682±8 Ma, thus timing the syn-Sybella tectonic fabric at around 1683 Ma. For implications concerning the tectonics of the area see stops 2.3 and 2.4.

Stop 2.3, Sybella Granite and May Downs Gneiss
Return to the May Downs Road, turn east, and down a track a few hundred metres from the Mosses Dam track for about 4 km, to a second area of prominent granite outcrops east of the track. The outcrops are Main Phase granite and "xenolithic hybrid granodiorite". Xenoliths include foliated quartzite and gneiss from the local Mount Guide Quartzite and May Downs Gneiss, indicating deformation and metamorphism had occurred before the intrusion of the granite.
We will walk east across the Mount Guide Quartzite for about 300 m to outcrops of May Downs Gneiss. These show pods of deformed and migmatized cordierite-Kfeldspar gneiss that have been truncated and replaced by sillimanite-biotite-Kfeldspar gneiss. The earlier gneiss is thought to have formed in the syn-Sybella event, with the later gneisses resulting from deformation at lower temperatures and/or higher pressures during the Isan D_2 event.

Stop 2.4, May Downs Gneiss and Mount Guide Quartzite, Big Sandy Creek
Return to the May Downs Road, head towards Mount Isa for about 6 km to the crossing of Big Sandy Creek. Turn south down a track just west of the creek for about 5 hundred metres to another crossing of Big Sandy Creek.
Just upstream of the crossing are migmatic gneisses with folds with shallowly-dipping axial planes. This outcrop is similar to others for which the migmatization and folding are interpreted as being syn-Sybella. A few hundred metres downstream is an outcrop of sillimanite-biotite-Kfeldspar gneiss with clear pseudomorphs after cordierite. The original cordierite gneisses are interpreted as forming in the syn-Sybella event and the sillimanite-biotite gneiss during D_2. Outcrops of gneiss immediately downstream show isoclinal folds, and are followed by Mount Guide Quartzite with some para-amphibolite

layers. Adjacent to this is strongly foliated amphibolite forming the base of the Eastern Creek Volcanics. This shows abundant folded lenses granite believed to be melted from the adjacent gneisses. The foliation is probably S_2.
The deformation history of cover sequences 2 and 3 in the Mount Isa Inlier is commonly interpreted in terms of the Isan Orogeny, around 1500-1600 Ma (e.g., Blake & Stewart, 1992; Bell, 1997; Bell & Hickey,1998; Page & Sun, 1998). However, it has been long known that an event must have preceded the deposition of the Mount Isa Group in the Sybella area, as basal units have locally cut down as far as Mount Guide Quartzite into cover sequence 2. The depositional high has been referred to as the Mount Gordon Arch (e.g., Derrick, 1982; Blake, 1987), and it is proposed that this formed in the syn-Sybella event at around 1672 Ma. This event was followed by deposition of the Carters Bore Rhyolite at 1678 Ma, and the basal Mount Isa Group at 1668 Ma (e.g., Jackson et al., 2005).

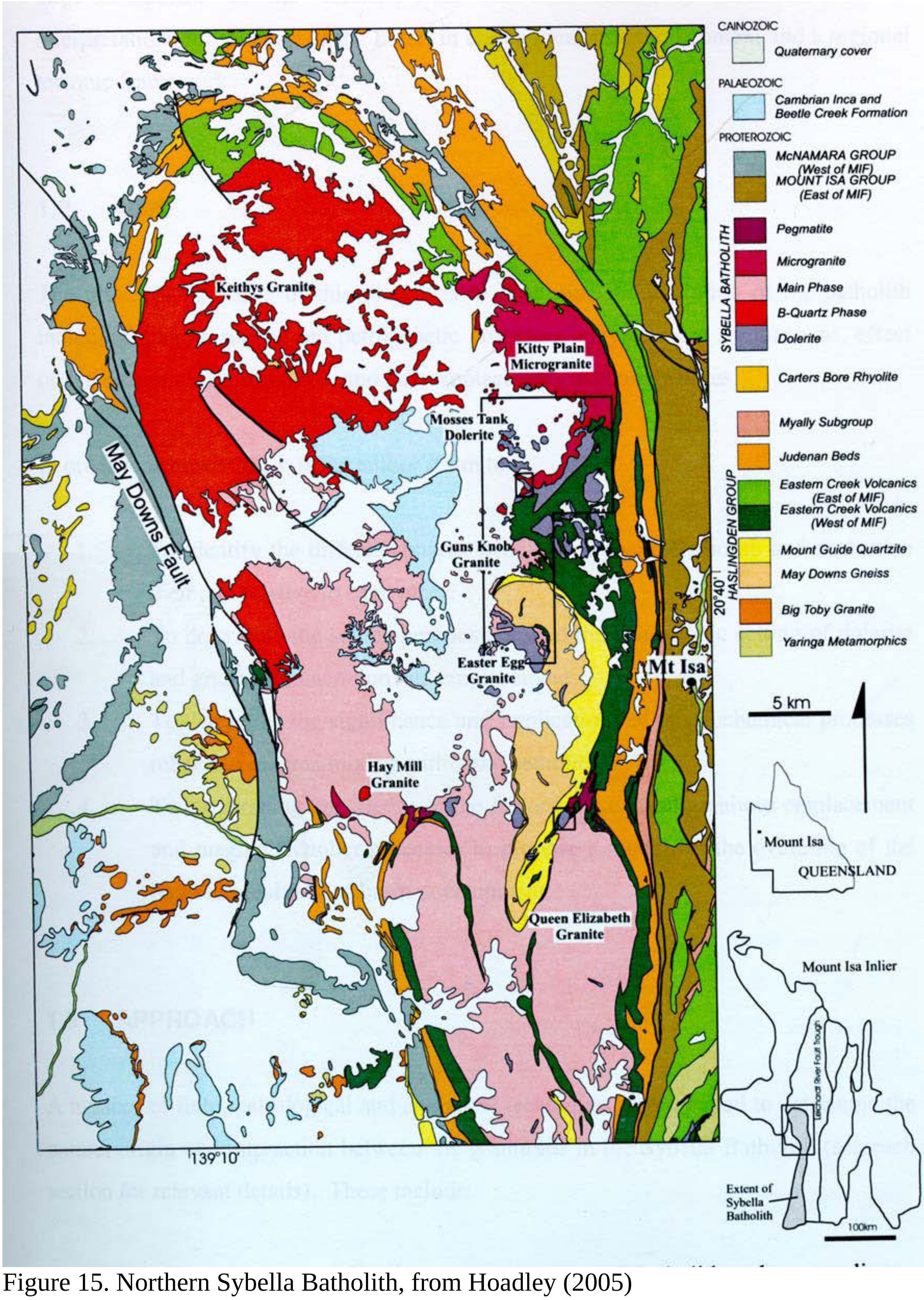

Figure 15. Northern Sybella Batholith, from Hoadley (2005)

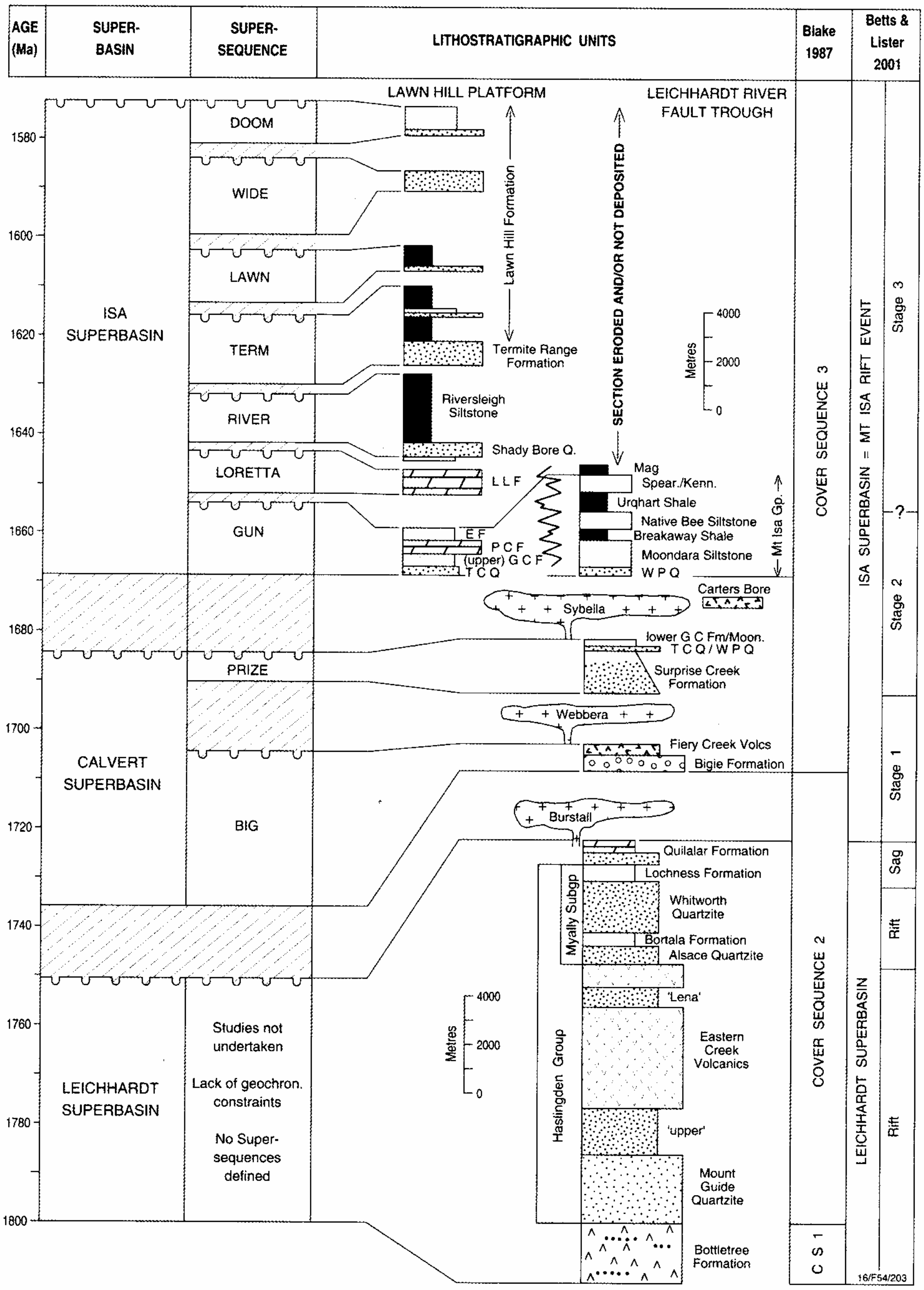

Figure 2 Regional chronostratigraphic chart for rocks aged between approximately 1800 and 1575 Ma in the Mt Isa Inlier. Lithologic columns in centre of diagram show simplified compositions for the respective lithostratigraphic units: LLF, Lady Loretta Formation; EF, Esperanza Formation; PCF, Paradise Creek Formation; GCF, Gunpowder Creek Formation; TCQ, Torpedo Creek Quartzite; WPQ, Warrina Park Quartzite; Mag, Magazine Shale; Spear, Spear Siltstone; Kenn, Kennedy Siltstone; Moon, Moondarra Siltstone. Two of the previous large-scale stratigraphic subdivisions used are shown on the right of the diagram (from Blake 1987; Betts & Lister 2001). Our preferred sequence-stratigraphic nomenclature is shown on the left. Major breaks in the rock record in the Calvert and Isa Superbasins, based on geochronological and geological information, are cross-hachured. See Figure 9 for rock type legend: v, mafic extrusive rocks; inverted v, felsic extrusive rocks; haphazard v, mixed extrusive igneous rocks; +, felsic intrusions; dark grey tone, shale and siltstone.

Figure 16. Revised chronographic chart for cover sequences 2 and 3, Mount Isa area, from Jackson et al. (2005). The amphibolite facies syn-Sybella event resulted in the Formation of the Mount Gordon Arch and onlap of Mount Isa Group on to the older units.

Stop 2.5. Spillway Fault.

1. Introduction: Late Faults of the Mount Isa Inlier

Some of the most prominent features of 1: 500 000 geological map of the Mount Isa inlier are NE and NNW - NW faults up to 200 km in length, which offset all pre-late Proterozoic geological features (e.g. Blake 1987). The NE set generally has right-lateral separations of up to 25 km, while the NNW - NW set has left-lateral separations of a similar order of magnitude. The Spillway fault is an example of the second set of faults.

The relative timing of the faults and their complementary senses of shear suggest that some of the faults in both the sets can be regarded as conjugate faults with an E-W shortening direction. Field observation confirms that some faults of the NE and NW sets are essentially pure strike-slip, supporting the contention that they may be conjugate. These strike-slip faults have some analogies with fault systems such as the San Andreas, and potentially offer insights into the mechanics of such fault systems.

2. Fundamental Problems of Fault Mechanics

The late faults in the inlier provide an opportunity to examine some fundamental problems of fault mechanics, such as:

1. Stress states and fluid pressures for faulting. The concept of low-friction faults was developed from studies of the San Andreas fault. Movement on this fault should produce a heat flow anomaly over the fault, given generally accepted coefficients of friction and stress levels (e.g. Lachenbruch and Sass 1980, 1988). However, there is no anomaly, and the so-called “heat flow–stress paradox” has been explained in two ways.

Firstly, the apparent orientation of contemporary maximum principal stress at a high angle to the fault trace led to the suggestion that the fault has a very low coefficient of friction (e.g. Mount and Suppe 1992). Alternatively, stress states around the fault may be influenced by high pore fluid pressures which would reduce the differential stress needed for fault slip, and explain the lack of a heat flow anomaly (Hickman et al. 1995). High pore fluid pressures require low crustal permeabilities. However, permeability measurements have been interpreted to suggest that the upper crust is inherently permeable on scales of 1 – 10 km, which would prevent pore fluid pressures from exceeding hydrostatic values (Townend and Zoback 2000), although hydrothermal cementation can dramatically and rapidly lower fault zone permeability (Morrow et al. 2002). This debate is summarised by “weak vs strong faults”, and the key evidence is the orientation of the maximum principal stresses relative to the faults.

2. Slip modes. Another major problem of fault mechanics is the nature of seismic faulting. Large segments of the San Andreas fault are creeping with intense, low magnitude seismic activity, while others are locked and appear to move by large slip increments in major earthquakes. There is no generally accepted explanation for this variation. The magnitudes of seismic slip suggests that slip increments could be visible in outcrop scale features. Large pressure changes that can be inferred from fluid inclusions can also indicate seismic behaviour.

3. Permeability structure of fault zones. The model by Caine et al. (1996) is commonly used to conceptualise fault permeability (Fig. 17). This model divides fault zones into a central core and a surrounding damage zone. However, the general applicability of this model is unclear, particularly to faults that have been reactivated and therefore may have inherited fault rocks.

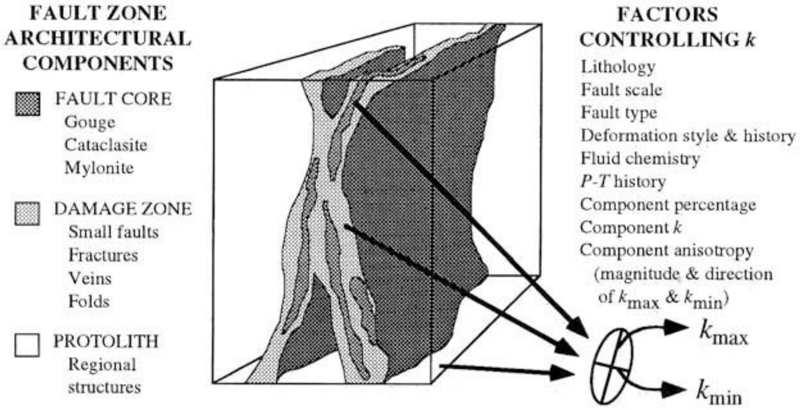

Figure 1. Conceptual model of fault zone with protolith removed (after Chester and Logan, 1986; Smith et al., 1990). Ellipse represents relative magnitude and orientation of the bulk two-dimensional permeability (*k*) tensor that might be associated with each distinct architectural component of fault zone. **from Caine et al. (1996)**

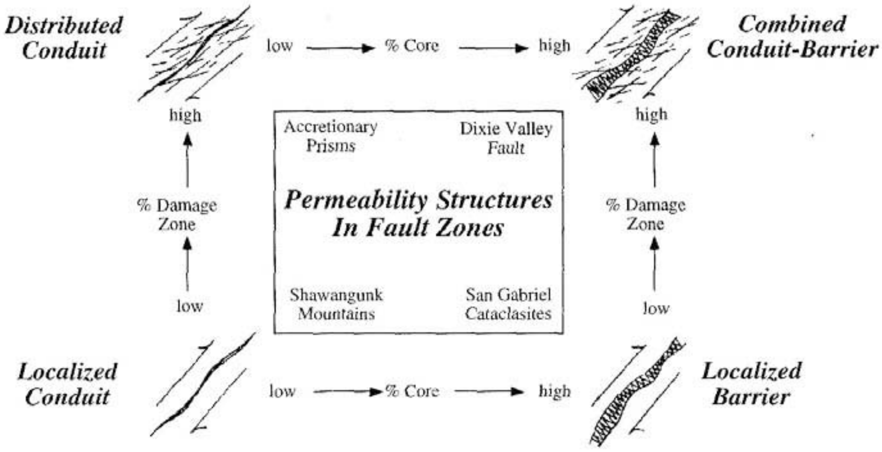

Figure 2. Conceptual scheme for fault-related fluid flow.

Figure 17. Conceptual fault models

3. The Spillway Fault

The Spillway Fault is visible in a superb three-dimensional exposure of faulted rock approximately 65m by 95m (E 139°31’10/ N 20°34’05) near Lake Moondarra, 15km NE of Mount Isa (Fig. 18). The major sub-vertical fault trends NW and is a prominent fault of the NNW trending group of the two conjugate fault sets. The area around Lake Moondarra contains two main sedimentary successions. The Haslingden Group to the SE unconformably overlain by the Mount Isa Group to the NW. The following descriptions are largely based on the honours thesis of Stark (2004).

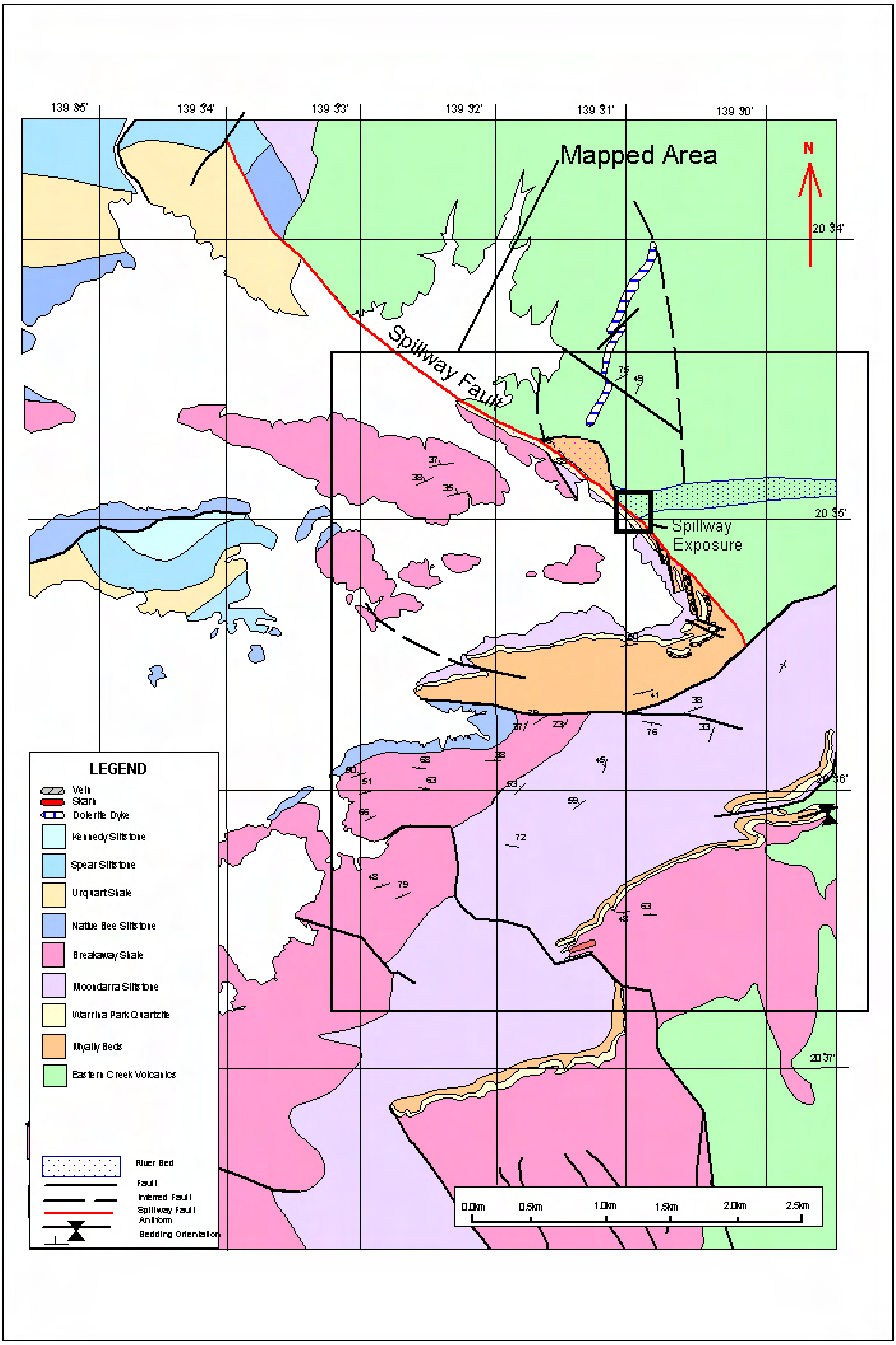

Fig. 18. Location map of the Spillway fault (Stark 2004)

3.1 Previous Work

Timing and geometry of the Spillway Fault was interpreted by Winsor (1982) who inferred that the Spillway fault was a D_1 fault folded around a D_2 anticline. The Spillway fault is one of three thrusts that comprise Bell's "Kokkalukkerrnurker Duplex" (1983, 1991), suggested to have formed during N over S D_1 thrusting, and subsequently folded by upright, N-S folds during D_2.

The observation of slickenline lineations on the fault plane of the Spillway Fault, which plunge at a moderate to low angle to the south-east is interpreted by Winsor as being a later phase of strike-slip movement on the Spillway Fault, possibly due to reuse of portions of the fault during post D_3 block faulting (Bell 1991). Other investigations of the Spillway fault and the local area were conducted by Bell and Hickey (1998), Dunnett (1973), Glikson et al. (1976), Proffett (1991), Plumb et al. (1980), and Windsor (1984; 1985).

3.2 The Spillway Exposure

Four main faults are observable on the Spillway Exposure (Fig. 19).

1. **The Thrust fault**. The NE fault is referred to as the Thrust Fault: it has down dip slickenfibres with a reverse sense of movement.
2. **The Spillway fault** occurs approximately in the middle of the outcrop. It is subvertical trending NW with an inferred left lateral sense of shear. A minimum sinistral separation of 400m is indicated by the displacement of the Myally Group sandstone marker bed (Fig. 18). The Spillway fault has 10 – 50 cm of fault gouge between two smooth bounding surfaces, within which P-foliation and Riedel shear are visible.
3. **The Diagonal fault** trends EW, and joins the Spillway fault: it has a sinistral separation of 15 m.
4. **The En Echelon fault**. A fault trending subparallel to the Spillway fault is observed on the western wall of the outcrop 2m below the baseline of the Spillway Exposure map (Fig. 4, 2m SE of grid reference 060/000). The fault trace is subvertical and similar in width to the Spillway fault. The fault fill contains pink gouge.

Zones of silicification and alteration mark the outcrop in several places. The most prominent of these zones being a breccia vein trending subparallel to the Spillway fault and located on its west side .

3.3 Kinematic and Dynamic Analysis

Combined analysis of all fault slip data from the Spillway, Thrust and Diagonal faults reveal a 95% compatibility, indicating that a single deformation event can still account for most of the measurements. The orientation of the maximum incremental shortening is E-W. However, there is a large difference observed between the minimum and maximum eigenvectors of the Spillway and Diagonal Faults. One possible explanation for this difference is that the Diagnoal fault formed due to the interaction between the Spillway and the En Echelon faults (cf. Segall and Pollard, 1980).

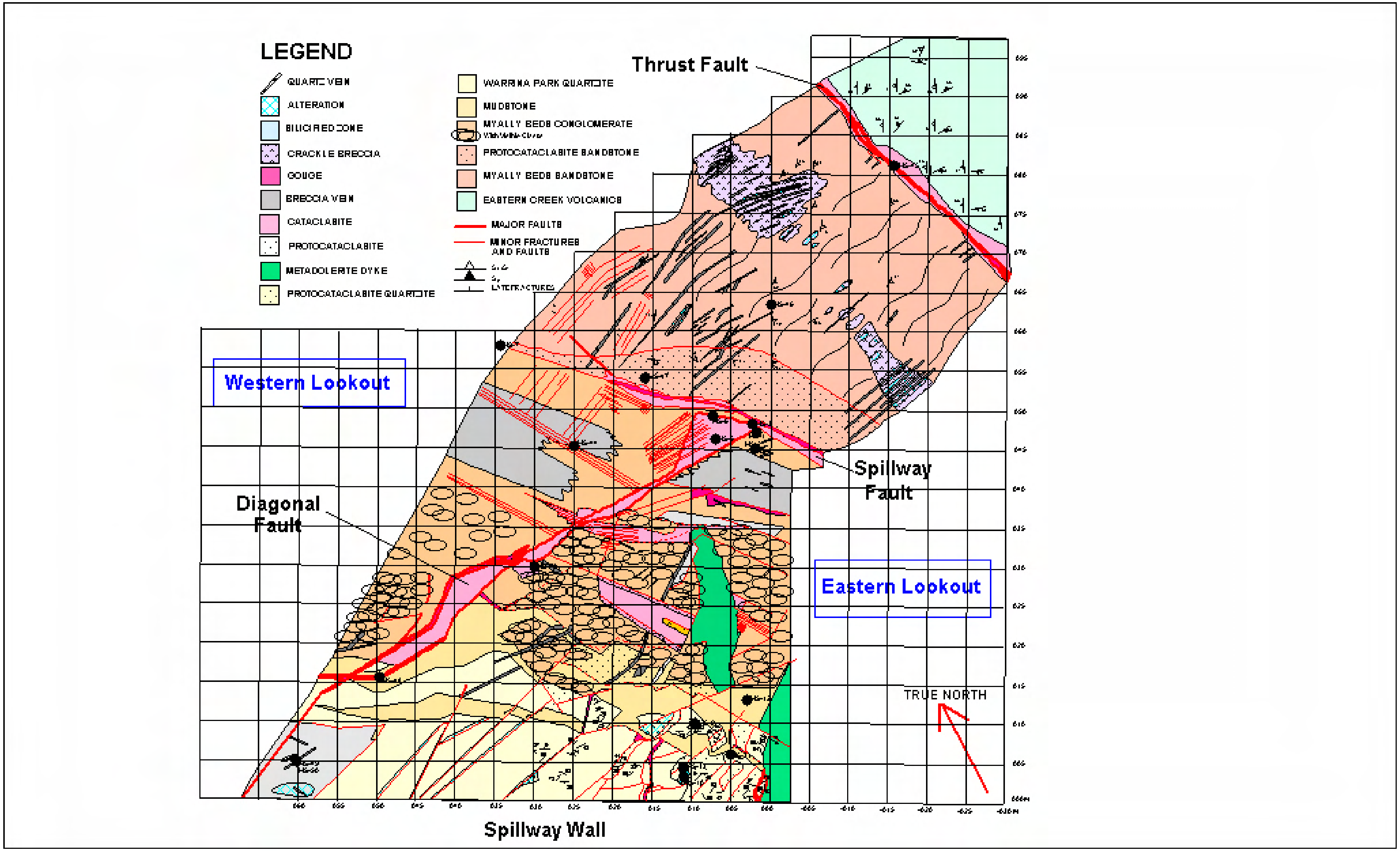

Fig. 19. Detailed grid map of the Spillway exposure (Stark 2004).

The Thrust fault may have formed at some time during the development of the Spillway fault and partitioned the convergent component of deformation. (cf. Aydin and Nur, 1982).

Approximately E-W extensional veins intersect the fault plane at an angle approximately 90º to striae on the Spillway fault plane, indicating that these veins could be extensional veins formed at the same time as the Spillway fault. This data is reinforced by the observation that the veins crosscut the protocataclasite related to the Spillway fault.

3.4 Fluid Inclusions and XRD Analysis

Fluid inclusions relating to primary crystal growth in quartz veins subparallel to the Diagonal fault generally have low minimum temperature (~200°C) and pressure of formation (<5 MPa), and low salinity (< 5 wt%). Inclusions relating to possibly recrystallised, quartz infill of the Diagonal fault have a greater range of minimum temperature of formation (81 – 396 °C) and minimum pressure of formation (240 - <5 MPa) and higher salinity (14-26.3 wt%). The high salinity may have been caused by the introduction of later, barite-rich fluids into cavities in the Diagonal Fault gouge, possibly not associated with the main stage of movement on the fault.

Boiling is suggested by the large number of completely liquid or completely vapour inclusions. The great abundance and small size of the fluid inclusions indicates that the fluid system was of a large volume and that crystal growth was rapid and resulted in porous, dendritic growth. This can lead to the formation of many, possibly smaller, primary inclusions, which is a characteristic of massive or bull quartz. These observations may be due to crystal growth of quartz occurring under boiling conditions. The thermometric data indicates that this quartz crystallized within 200m of the surface, A recrystallised chalcedonic micro-plumose texture in quartz grains of the same morphology, indicates that there was significant fault related deposition of quartz in the chalcedonic zone within 300m of the surface (described by Morrison et al., 1990).

Samples of fault gouge from the Diagonal and Thrust Faults analysed using X-ray diffraction are very similar in composition, indicating these faults may have formed under similar conditions. Both are dominated by quartz, albite, kaolinite, ilmenite and muscovite. This may provide further evidence that the faults formed at the same time.

3.6 Structural History of the Spillway Exposure and implications for fault mechanics

A complex and interrelated history of movement can be deduced for the Spillway outcrop (Fig. 20).

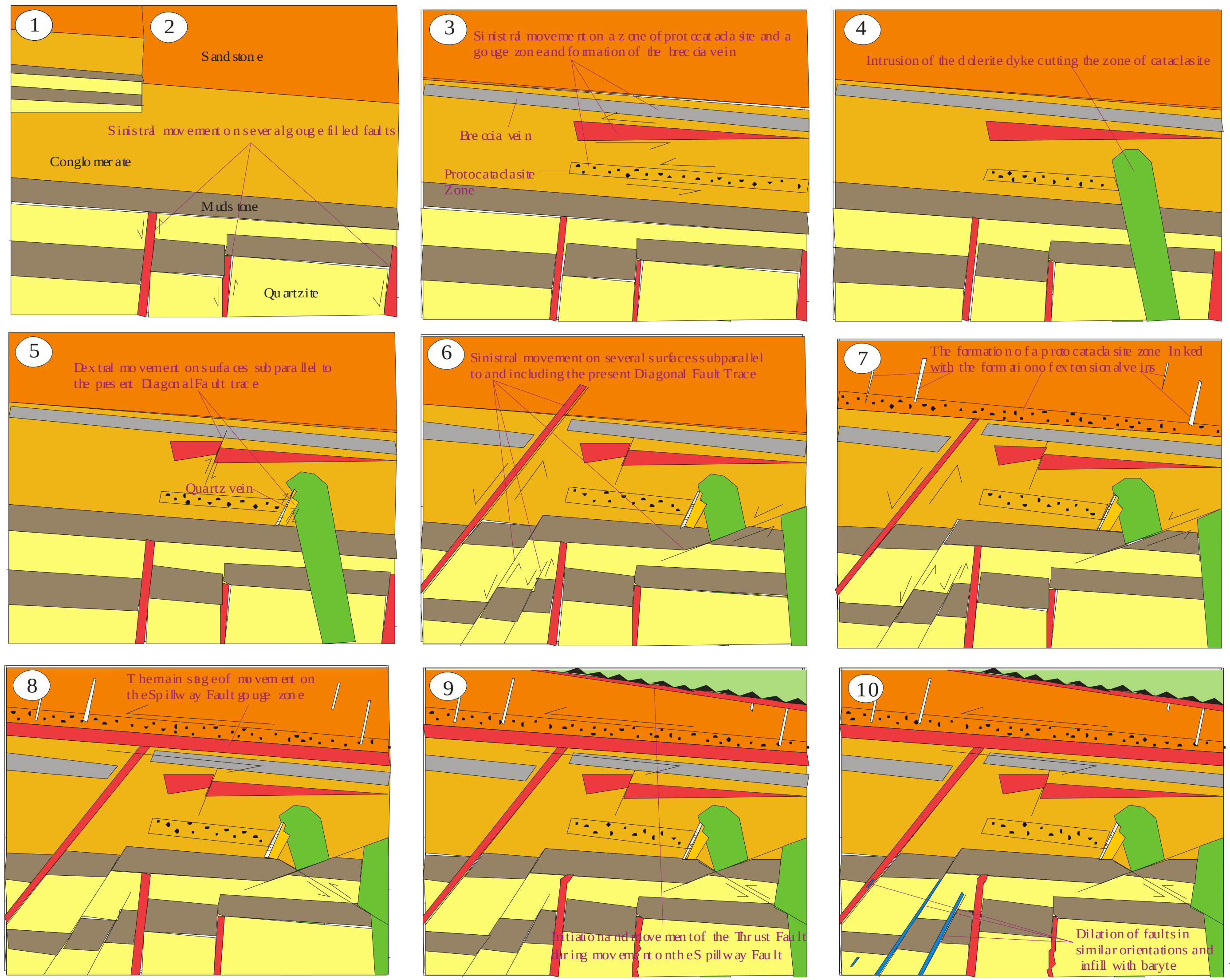

Fig. 20 Structural history of the Spillway fault (Stark 2004)

The high angle of the extensional veins to the Spillway fault indicates either that it was weak, or that pore fluid pressures were high. The importance of pore fluids in faulting is suggested by extensive veining and alteration on the outcrop, but severe limits are placed on the pore fluid pressures by the epithermal textures of the veins, showing that faulting occurred within a few hundred m of surface.

Despite the excellent exposure, the Spillway exposure does not offer any obvious clues about slip mode. Although features such as Riedel shears and slip surfaces have been interpreted to indicate seismic slip because such localisation phenomena also form in experiments during rapid sliding, such an inference is dubious, not least because of the severe problems in extrapolating experiments to nature. Incremental histories of vein opening/shear are sometimes also advocated as indicators of paleoseismicity, but they are lacking in this outcrop. The outcrop illustrates the typical difficulties of investigating paleo-slip modes, and should stimulate discussion on the subject.

The Spillway exposure is an example of a fault zone that may have had a long and complex history. The simple concept of a fault core and damage zone can not be applied to this fault zone, which shows instead the interaction of a number of fault segments, each with its own core and damage zone, and intervening zones of great permeability heterogeneity. The progressive history indicated in Fig. 20 shows that fault reactivation and the segmented structure of the fault zone need a more sophisticated understanding of fault zone permeability. This is likely to be true for any faults that have been reactivated faults - perhaps indeed for most faults.

Stop 2.6. Eastern Creek Volcanics

Roadside, a few hundred metres NW of the Spillway Fault (Drive along the one-way loop past the Lions Youth Camp near the Spillway- the outcrops are on the western return loop).

Outcrops here are greenschist-facies Eastern Creek Volcanics. They include mudstones, cross-bedded quartzites, flows with flow-top breccias, and epidozites.

DAY 3. DEFORMATION IN THE KALKADOON/LEICHARDT BLOCK, THE WONGA BELT, AND CORELLA FORMATION.

Stop 3.1. Leichardt Volcanics and Kalkadoon Granite.
Highway east of Mount Isa, 5.5 km east of Gorge Creek, just past Dingo Creek. The outcrops are typical cover sequence 1, Leichardt Volcanics and Kalkadoon Granite. The volcanics are interpreted as being originally porphyritic acid volcanics, possibly ignimbrites. All lithologies show a strong subvertical foliation and a steeply plunging lineation, believed to have formed during the Isan Orogeny D_2 event. The Kalkadoon-Leichardt Block does not contain useful pelitic rocks, but Foster (2003) determined temperatures and pressures typical of the low-pressure amphibolite facies of the Mount Isa Inlier, using new calibrations of geothermobarometers in amphibolites. The deformation and metamorphism is important, as it is not consistent with the D_2-related thrust models (e.g., O'Dea et al, 1997; Giles & MacCready, 1997; Goleby et al., 1998) that postulate the block to be a buttress.

Stop 3.2. Multiple deformation, Corella Formation.
Drive about 22 km further east along the Highway. Walk a few hundred metres south along an old track to a large dark outcrop of Corella Formation, situated among ridges of Ballara Quartzite. The rocks are marble and scapolite-rich biotite-Kfeldspar-calcite-quartz calcsilicate rocks (formerly dolomitic shales). The abundance of scapolite strongly suggests a shallow marine evaporitic environment. The metamorphic grade is upper greenschist to lower amphibolite facies. The abundant north-south folds with steep axial planes are mainly F_2. Refolded F_1 folds are present, as are steep EW spaced solution cleavages (S_1).

Stop 3.3. Wonga Granite and Wonga Belt, Greens Creek.
Continue east along the Highway to about 8 km past the Mary Kathleen turnoff, just past the roadside "camping grounds". Drive south along the track to Fountain Range to the Greens Creek crossing, almost 500 m from the Highway. Outcrops to the east and west of the crossing show deformed Wonga Granite, showing magma mixing/mingling and deformed enclaves. The shapes of the enclaves will be examined, as their consistent orientation in the foliation, combined with a lack of folded enclaves, could imply that it of combined magmatic-tectonic derivation. Less deformed outcrops show euhedral Kfeldspar phenocrysts, also suggestive of magmatic flow. Some outcrops show S-fabrics, whereas others show strong lineations. Folded leucocratic dykes are also present that contain the strong fabric, which is axial planar to the folds. Assimilation of amphibolite lenses and intrusion of ?metasdeiments, which also have the strong NS fabric, can also be seen.
The Wonga Belt is a narrow NS zone of intense deformation and amphibolite facies grade. The granites intruded around 1730-1750 Ma, with at least some deformation and metamorphism synchronous with intrusion. Oliver et al. () argue that the main foliation of the Wonga Belt formed in an extension event, the generally steep orientation shown by most outcrops being a function of subsequent D_2 deformation in the Isan Orogeny. In contrast, Bell et al. () argue that the Wonga Belt is a shear zone that marks the eastern

boundary of a D_1 thrust belt. If the sub-vertical fabric is magmatic to solid state transitional fabric, there are important consequences for both alternatives.

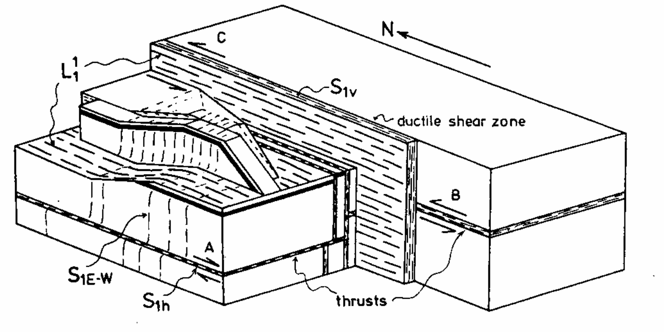

Figure 21. Model of Bell et al., (1992), for the development of the Wonga Belt

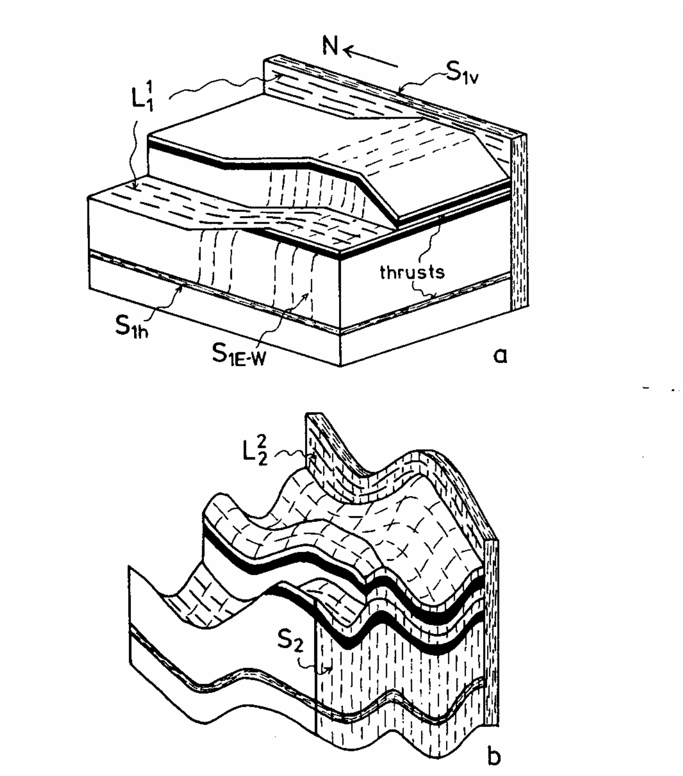

Figure 22. Model of Bell et al., (1992), for the development of the Wonga Belt in D_1, with subsequent folding in D_2.

Stop 3.4. Foliations and metasomatism, Corella Formation, Rosebud Dam.
Continue about 3 km past Greens Creek to the Rosebud Dam (Fig. 23). Sillimanite-zone calcsilicate rocks of the Corella Formation are well exposed below the relicts of the dam wall. They show spectacular spaced solution cleavages, formed by a combination of gaping, calcite infill, and reaction of calcite with the otherwise calcite-depleted wall-rocks to form amphibole or pyroxene. Such cleavages can be seen as axial planar to an F_2 fold, but S_1 and S_4 cleavages are present, along with the dominant S_2. We will also see a variety of calcite veins and lenses, including en echelon lenses filled with pink calcite. Also present is a small calcite "pipe" with albitization and minor chalcopyrite development in the adjacent wall-rocks. Such calcite pipes are abundant in the Mary Kathleen region (Figure 26), and are described in Oliver (1995) and Oliver et al. (1990). Scapolite development in metadolerite bodies will be examined.
Just west of the dam are layers of andalusite/sillimanite schists. A further 100 m west are large outcrops of cordierite-anthophyllite, cordierite biotite, and cordierite sillimanite rocks, interpreted by Reinhardt (1987) as due to metamorphism of high-Mg clays which are associated with some evaporitic dolomites elsewhere in the world. The unusual foliation in the cordierite-anthophyllite rocks will be examined. The occurrence of kyanite in localized retrograde shear zones lead Reinhardt (1992) to propose an anticlockwise P-T-t path.

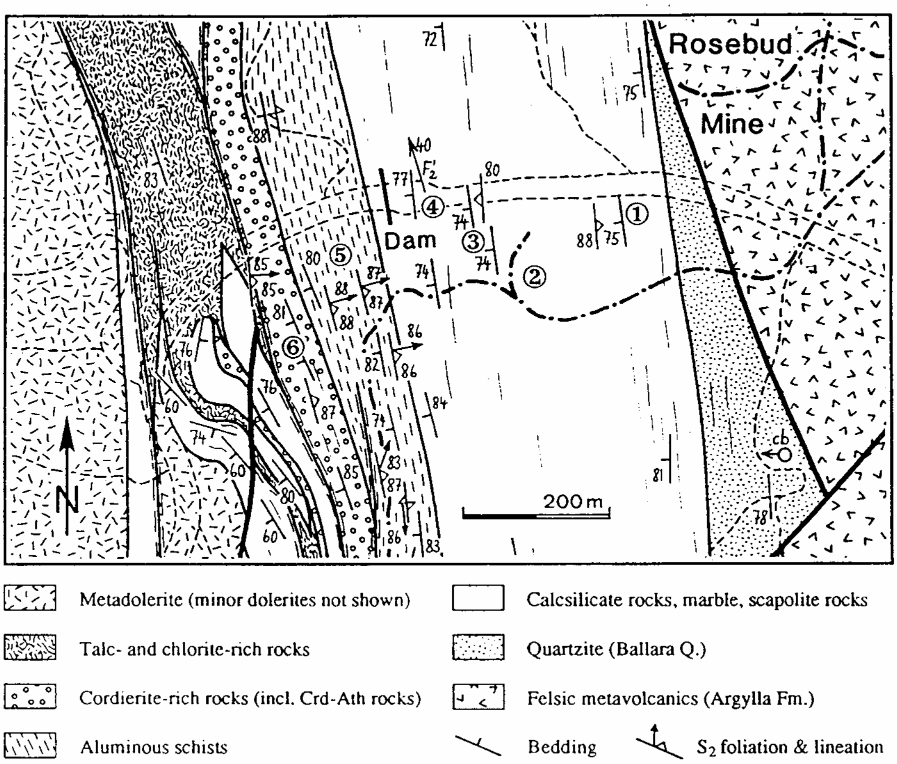

Figure 23. Map of the Rosebud Dam from Reinhardt (1992). Locations 3-6 will be examined.

Stop 3.5. Fountain Range Fault

Continue around 15 km south of the Rosebud Dam at Fountain Spring.

The Fountain Range fault trends NE and is over 150 km long. It is the most prominent member of the NE striking late fault set, and has dextral separation of ~ 20 km. It is one of the most spectacular features of the inlier visible from the air, because the central segment of the fault forms a protrusive ridge. The late faults are prominent geomorphological features where they have slight bends: right bends on NE, dextral faults and left bends on NW, sinistral faults, in both cases corresponding to releasing bends for an inferred EW shortening and maximum principal stress.

The fault fills in the releasing bends are fine grained grey, white or pink quartz, quartz veins, breccias and gouges, indicating a significant dilational component of movement. At Fountain Springs, we are able to see the periphery of the fault fill, where it consists of a fine-grained quartz cut by numerous mm to cm wide short quartz short veins that have been commonly deformed by subsequent fracturing. These veins and vein fragments comprise up to 40% of the rock. Most of them have a massive homogenous filling suggesting a single opening and filling event. Some have syntaxial fillings with euhedral quartz crystals, and others have crustiform banding. The vein orientations have a weak grouping into two sub-vertical sets, trending NS and EW (Fig. 24). Veins also occur sub-parallel to the Fountain Range fault.

Around the Springs outcrop, sub-vertical fractures parallel to the ridge with lengths of 10’s of m and spacings of 0.5 – 1 m are common. They have filling of quartz, clay or breccia, and may have slickensided surfaces with gently plunging slickenlines.

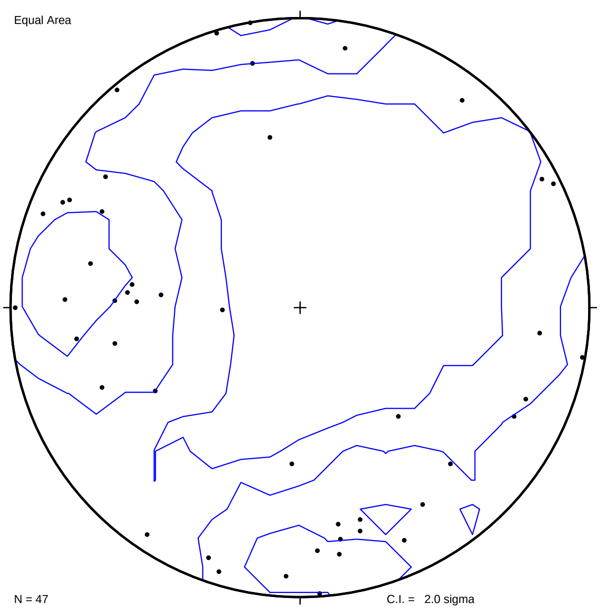

Fig. 24. Lower hemisphere, equal area stereoplot of poles to veins on the Fountain range fault at Fountain Springs. Kamb contour, significance level 3σ, Contour Interval 2σ.

A calculation based on the volume of quartz in the fault zone of the Fountain Range fault indicates an estimated 1.68 x $10^{11}m^3$ of pure water could have deposited this quartz over the period the fault was active (Stark 2004). This volume of fluid flow is comparable to contemporary estimates of fluid flow volumes required to precipitate major gold deposits (Phillips et al., 1987).

In several similar faults (e.g. the Overlander Fault to the east of the Fountain Range fault, the Spillway fault), the vein filling that occupies much of the fault zone has excellent euhedral infill textures and a bladed habit, which can be interpreted as quartz replacing calcite, indicating boiling. Both these features are typical epithermal textures, indicating that the fault filling was emplaced under in near surface conditions.

The vein set trending ~ E-W, in the inferred direction of shortening during faulting, is a common feature of several of the late faults (cf. the Spillway fault). These veins both cut and are cross-cut by fault-parallel veins. Sibson et al. (2003) have interpreted the coincident fault-parallel and oblique vein sets as indicative of alternating stress states during seismic cycles: the E-W veins may form when σ_3 is oblique to the fault in the interseismic stage, while σ_3 is perpendicular to the fault in the post-failure stage when shear stress has been nearly totally relieved.

A major question for the geological history of the Mt Isa inlier is the timing of the fault movement and infill on the late faults. The pertinent observations are:

1) Contemporaneous dextral movement on NE and sinistral movement on NNW to NW faults suggests E-W shortening
2) Epithermal fault filling textures show that fault filling occurred at near surface conditions
3) The volumes of infill require large hydrothermal fluid systems
4) The undeformed Lake View Dolerite intrudes part of the Fountain Range fault: this dyke has been dated at 1100 Ma
5) Some movement on the NNW-trending Cloncurry fault occurred in post-Jurassic times
6) Although the Cloncurry fault does contain fault fill textures similar to the other faults, these textures are not present where the fault cuts post-Jurassic rocks.
7) A suite of characteristic quartz-K-feldspar-hematite veins, along and adjacent to the Cloncurry fault, have oxygen isotope compositions that are compatible with quartz precipitation from low-latitude meteoric waters.
8) The polar wander path of Australia suggests low-latitudes at 1100 Ma and ~ 600 Ma and possibly 360-340 Ma (Mark et al. 2004).
9) Exhumation to depths of < 5 km had occurred by the Cambrian (Spikings et al. 1997, 2001).
10) No large differential vertical movement occurred on major tectonic boundaries within the inlier after 350 Ma (Spikings et al. 1997).

Points 2 and 7 – 10 are compatible with faulting during the Alice Springs orogeny, but the NS shortening of that event is incompatible with point 1. Because the quartz-Kfeldspar veins described in point 7 are restricted to the vicinity of the Cloncurry fault, their relevance is questionable. A late Isan orogeny timing remains possible for the fault movement, and is most compatible with the E-W shortening direction. Such a scenario can is also most compatible with the need to invoke large-scale hydrothermal systems.

DAY 4. MARY KATHLEEN SYNCLINE, MARY KATHLEEN MINE, CORELLA BRECCIAS, D_1 THRUST, FOLDS IN JASPILITES

Stop 4.1. Folds in marble, Mary Kathleen Syncline.
About 6 km east of Mary Kathleen turn north of the highway though a gate about 3km to another gate, then a few hundred metres to a large outcrop of marble with interlayered calcsilicate rocks. This is a geological monument so that hammering and sampling are not permitted. Well-developed F_2 folds show layer thickness control. Some spectacular examples of elastica folds in some of the marble layers can be seen. The calcsilicate layers contain grossularite, and more rarely wollastonite and vesuvianite, indicating fluid infiltration and quite low X_{CO2} conditions. On the basis of stable isotopes, it is argued by Cartwright & Oliver (1994) that the calcsilicate minerals formed by contact metamorphism during the emplacement of the 1735-1740 Ma Burstall Granite and the mineralogy remained essentially unchanged during D_2.

Stop 4.2. Mary Kathleen Mine
Turn off the highway on the road that passes the former town site. The track to the mine leaves the eastern side of the road about 6 km past the town site, 200 m from the end of the bitumen.
We will examine highly deformed calcsilicate rocks and pegmatite bodies immediately west of the Mary Kathleen Shear Zone, sense of shear indictors associated with clasts within the shear zone, the syn-intrusion (~1740Ma) breccias and garnet-clinopyroxene skarns, and ore veins consisting of garnet, allanite and minor uraninite in late fractures. The mining of the orebody, with 10000 tone of U_3O_8 and large tonnages of REE, commenced in 1956 and continued intermittently until 1982. 1500-1550 Ma U-Pb dates were obtained from the ore (Page, 1983), and a 1580±50 Nd-Sm age on the altered skarn in the orebody (Maas et al., 1988). It is argued by Oliver et al. (1999) that the ore was concentrated from the original skarn during the Isan Orogeny. During movement on the Mary Kathleen Shear Zone, ductility contrasts between the skarn and the deforming calcsilicate rocks allowed development of curved fractures in which the ore was localized (Figure 25).

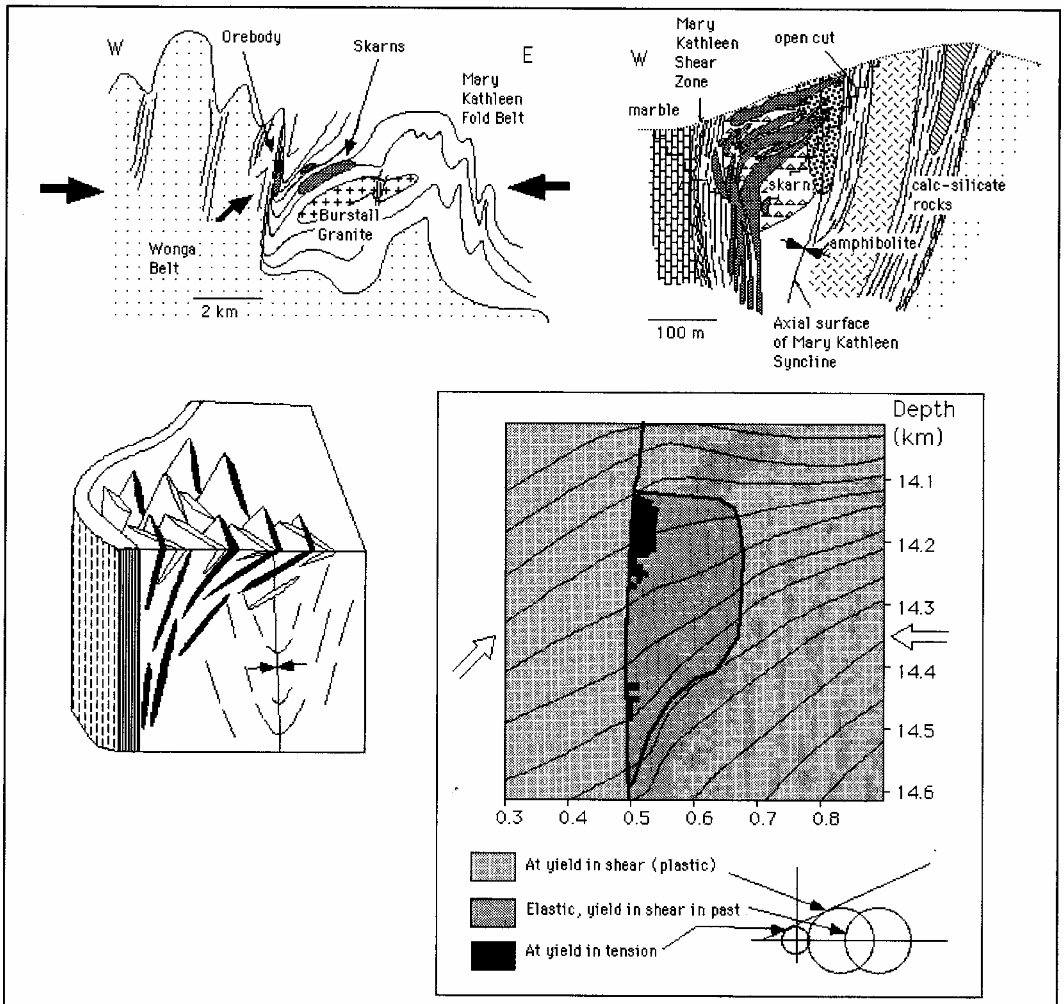

Figure 2: (Modified in part from Oliver *et al.* 1999). Geology and numerical model of the Mary Kathleen U-REE deposit. Top: regional and local cross section of geology showing position of orebody relative to regional structures, ore shoots in host skarn, progressively steepening down and to the west as the Mary Kathleen Shear Zone is approached, Bottom: Coceptual 3D model for development of variably dipping ore shoots by coupling of the shear zone with the skarn body during combined shortening and shear, and numerical model (using FLAC) showing how predicted stress field approximates the observed ore shoot dips in 2D.

Simplified input and 3 "snapshots" of the numerical modelling (start, middle and end of the runs), showing weaker shear zone rocks to the west, "hard" skarn in the middle (hosting later ore veins), and moderate strength and permeability calc-silicate rocks and amphibolite to the east, along with boundary conditions (shortening + pure shear on western boundary, shortening only on east. c) Summary of results for enlargement of the final run, showing curved lines of the trajectory of σ_1, varying in a fashion similar to the variation in the geometry of the ore shoots, and variation in the failure mode, which is a rough approximation of the ore grades at broad scale. These correlations vindicate our interpretation that ore shoots formed by coupling of the shear zone with the hard skarn body during deformation.

Modified from Oliver. N. H. S., Ord, A., Valenta, R. K. and Upton, P. 2001. The role of rock rheological heterogeneity in fluid flow and ore genesis, with examples and numerical models from the Mt Isa district. In: (Tosdal, R., Richards, J., eds.) *Structural controls on ore deposits*. Society of Economic Geologists, Reviews in Economic Geology, 14, 51-74.

Figure 25. Model for the Mary Kathleen ore deposit, from Oliver et al. (2001)

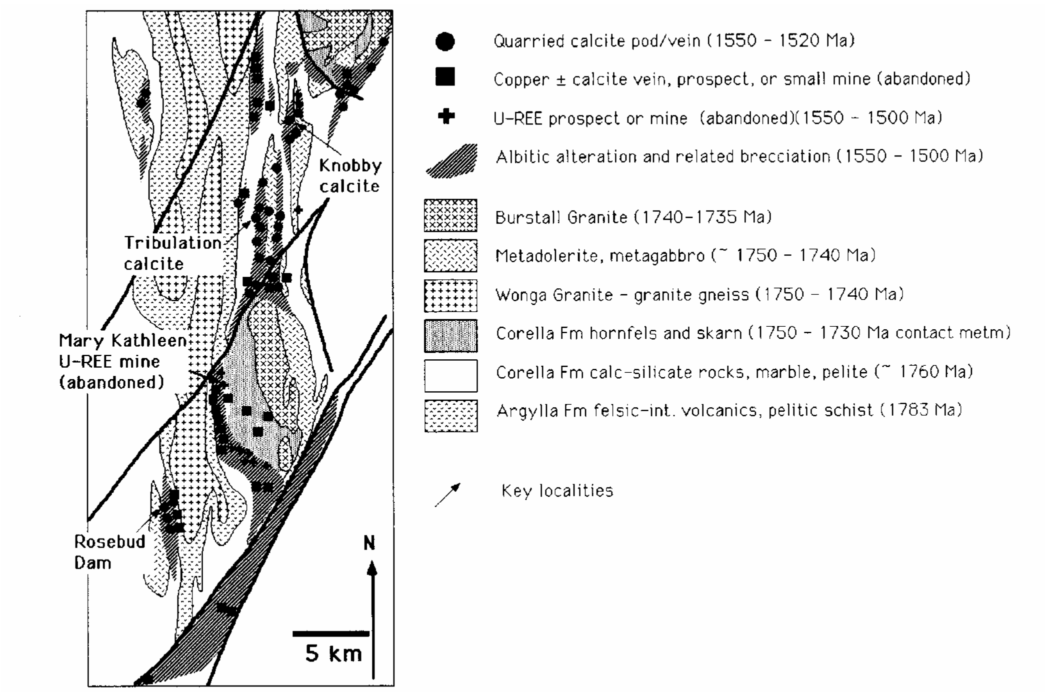

***Figure 2:** Geological map of a portion of the Mary Kathleen Fold Belt, showing the general distribution of podiform calcite veins (circles), copper prospects (many also hosted by veins), and U-REE mines and prospects. These are associated with elongate strips of albitised rocks, as indicated by the cross-hatching. For further details of albitisation, see Oliver et al. (this volume, b).*

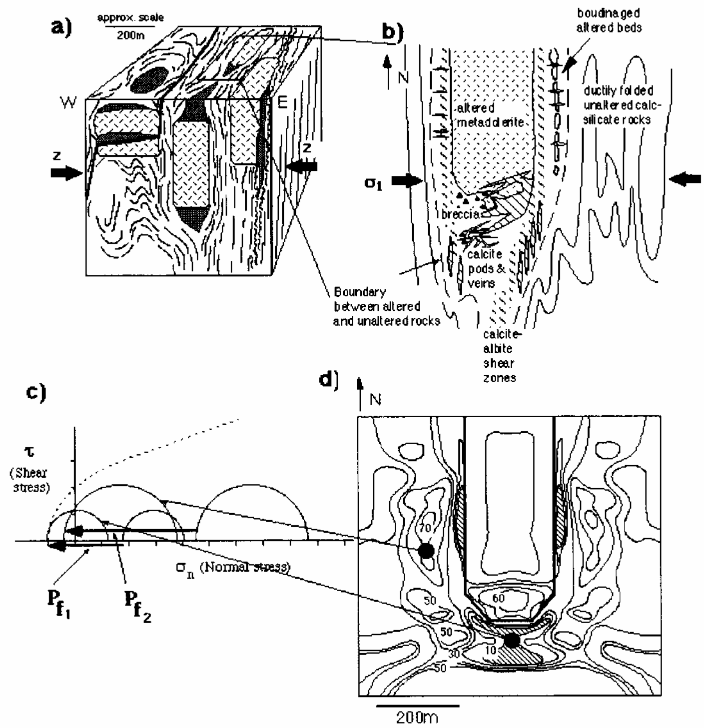

Figure 26. Calcite pipes in the Mary Kathleen area, from Oliver et al. (2001).

Stop 4.3. Breccias and intrusives, Butchers Creek
Butchers Creek crosses the Flinders Highway about 15 km west of Cloncurry. Prominent outcrops occur a few hundred metres south of the road. The first outcrops are of breccia consisting of relatively small pink fragments of albitized Corella Formation in a largely albitic matrix. This is followed by a small body of granite on the western bank and an altered gabbro on the eastern side of the creek. These are followed further south by breccia that in places has large granite clasts. Layering in many breccia outcrops are probably relicts of the bedding.
To the east and south of the Butchers Creek area the entire outcrop of Corella/Doherty Formation shows extensive brecciation, with considerably more than 70% of outcrops showing breccia development and hydrothermal alteration. Associated hydrothermal alteration. This contrasts with the Mary Kathleen region where less than 25% of outcrops of Corella Formation are brecciated. Many of the breccias show intimate relationships with intrusives of the ~1500-1535 Ma Williams and Naraku Batholiths such as spatial association, clasts of igneous rocks in breccia, and breccia carapaces around some intrusive bodies.

Stop 4.4. The Overhang Shear and folds in the Overhang Jaspilite
Proceed 26 km down the road to Duchess, turning down a track to the east for 6 km, keeping to right forks. Walk about 200 m west of the track to a prominent siliceous outcrop. The outcrop is interpreted by Ailleres & Betts (1997) as being a silicified shear zone (the Overhang Shear Zone) marking the boundary between the Marimo-Stavely Block to the east and the Overhang Jaspilite to the west (Fig. 27). ESE-trending F_1 folds are interpreted as having been rotated into the shear zone (Fig. 28). The shear zone was subsequently folded by roughly NS F_2 folds such as the Duck Creek Anticline (Fig.29). On the western side of ridge numerous boulders of folded haematite-jasper are found in a creek feeding off outcrops of Overhang Jaspilite from the ridge further west. Similar-style folds are the most abundant.

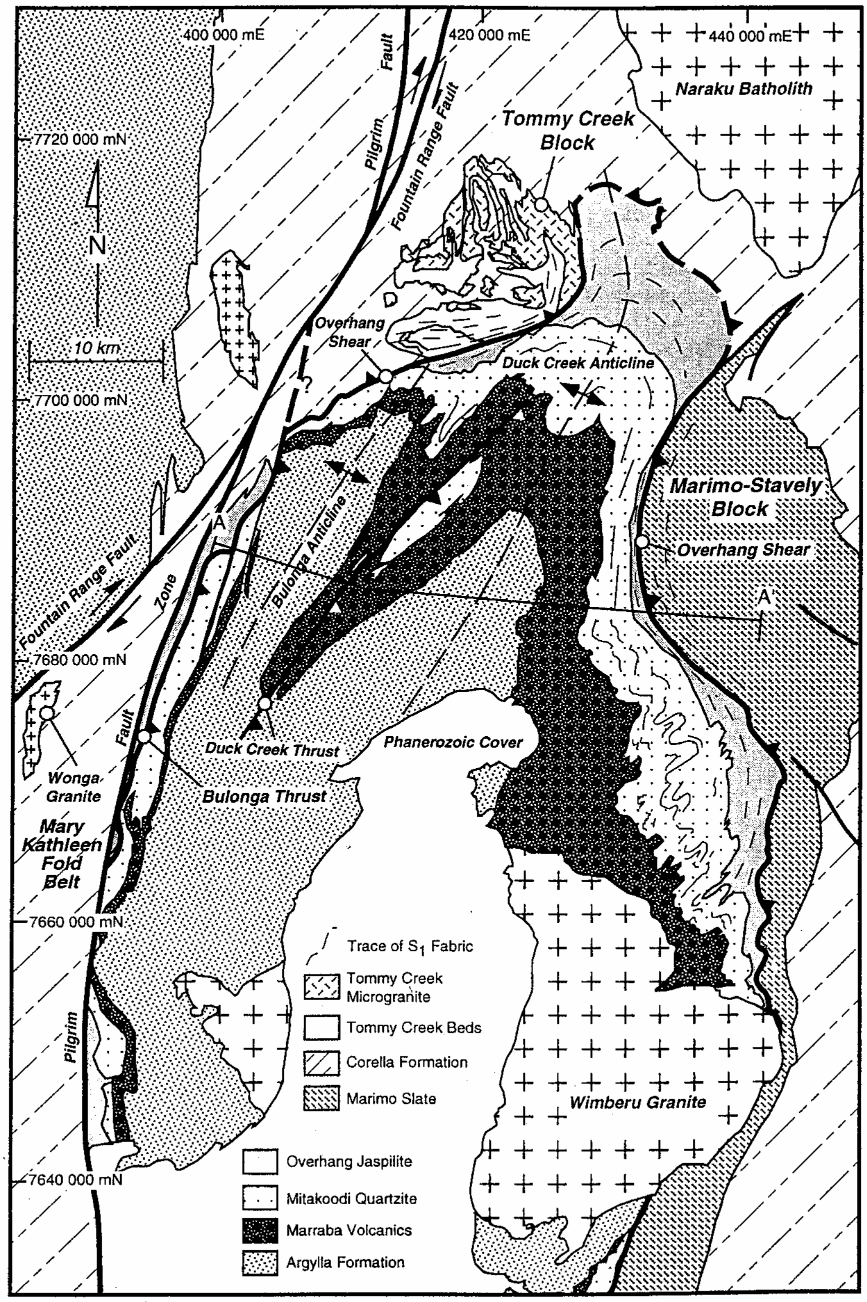

Figure 27. Map of the Duck Creek Anticline area showing the Overhang Shear, from Betts et al. (1997)

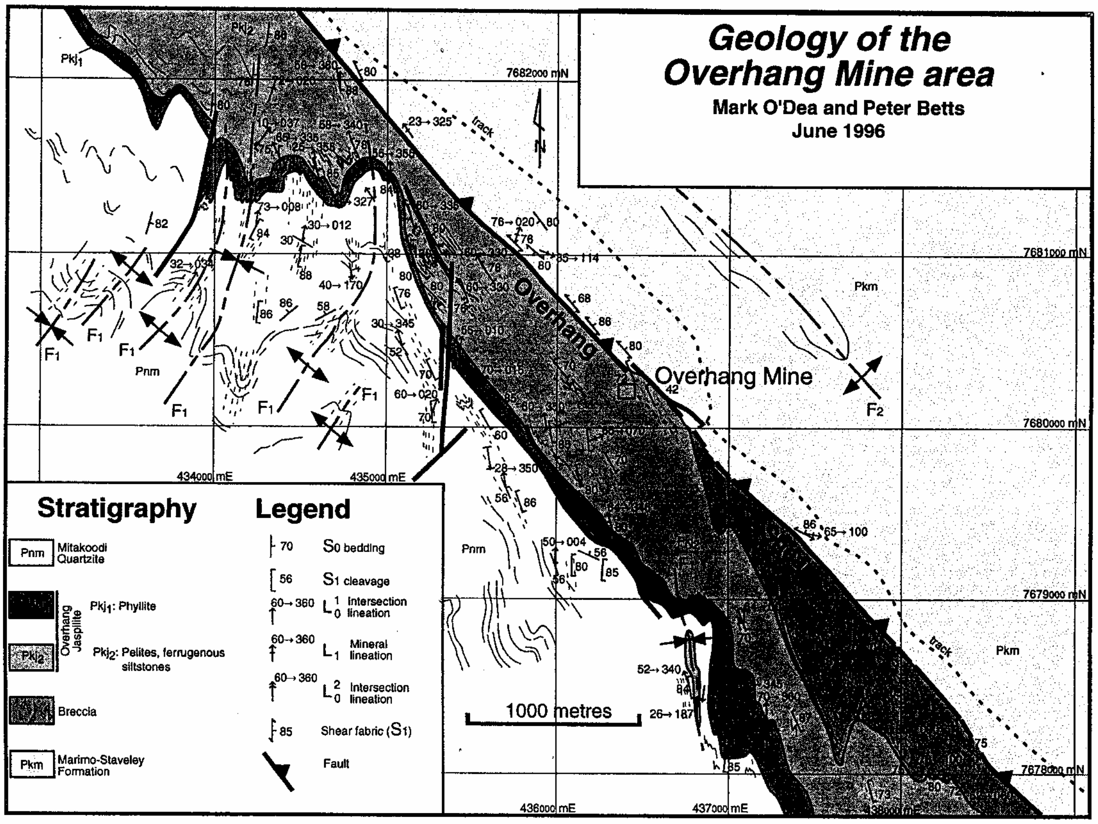

Figure 28. Map of the Overhang Mine area, showing the Overhang Shear and rotation of F_1 folds into the shear, from Betts et al. (1997).

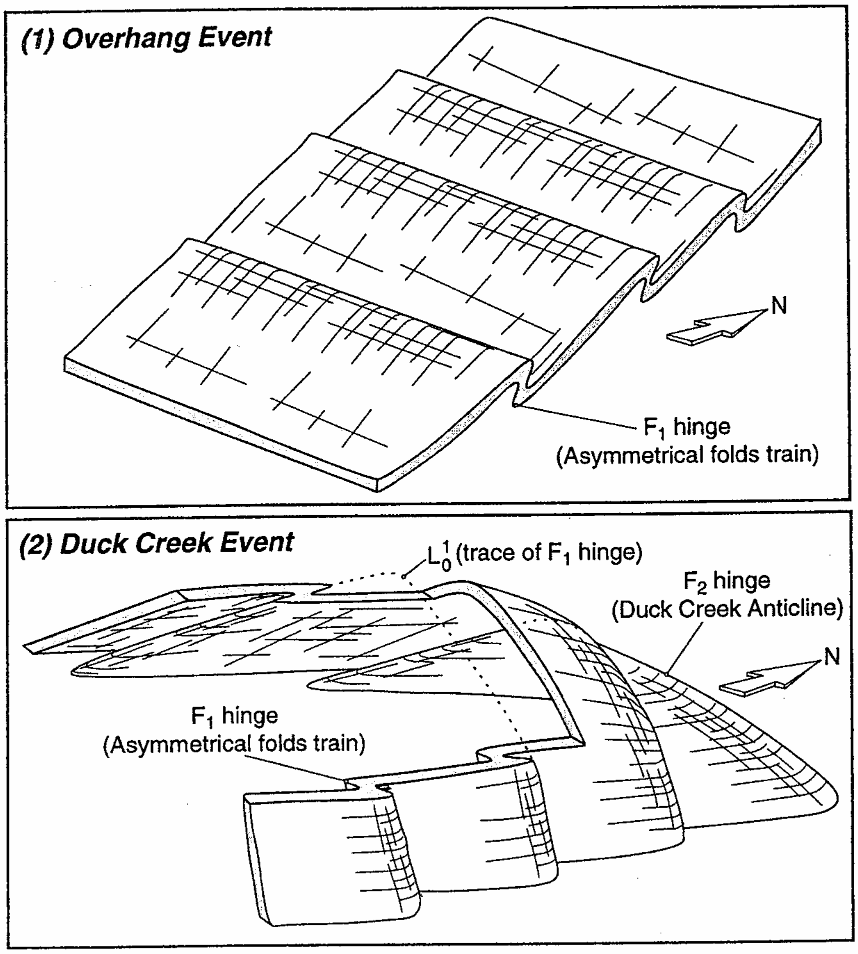

Figure 29. Model for the Overhang Shear and F_2 folding, from Betts et al. (1997).

DAY 5. SNAKE CREEK ANTICLINE. FOLDS, PORPHYROBLASTS, ALBITITES, BRECCIAS.

Stop 5.1. Roxmere Waterhole. Several Types Of Breccias, Actinolite Veins, Albitization.

Drive to the Roxmere waterhole, on the Cloncurry River a few km south of the homestead.

Introduction

This superb exposure shows different types of breccias in the Corella formation, and their relation to each other, and to the regional deformation history. A central aim on this outcrop will be to provoke discussion about the mechanisms of brecciation, bearing in mind that as much as half to Corella formation in the Eastern Fold belt is mapped as brecciated. The brecciation mechanisms are a fascinating and important geological question: the orebody at Ernest Henry Copper-Gold mine, 38 km NE of Cloncurry, (open pit resource of 108 Mt @ 1% Cu and 0.5g/t Au) is hosted in breccias similar to some of those seen at this outcrop.

2. Type I breccia

At the southern end of the outcrop, cm – dm scale layering of typical calc-silicate Corella formation (K feldspar, actinolite) is folded into tight folds with upright NS axial surfaces – a general D2 style of deformation. However, the individual layer of calc-silicate have been fractured and boudinaged around the fold hinges (Fig. 30), and zones of more brecciated rock form in axial planar orientations. These are typical Type I breccias in which the original bedding is still largely intact.

Fig. 30. Type I calc-silicate breccia in the Corella Formation: note fractures around outer arc of fold. Roxmere waterhole.

Fig. 31. Wave-like fragment boundaries. Roxmere waterhole.

These breccias are characterised by angular fragments, a high clast-matrix ratio, and poor sorting. Adjacent fragments have commonly rotated and been transported little, so that they can be reconstructed to their original geometry. The matrix is a combination of infill (actinolite, magnetite) and clast fragments. Fragment boundaries are commonly sharp and wave-like (Fig. 31).

Type I brecciation mechanisms

The outer arc extension fractures (Fig. 30) and axial planar orientation of the breccia veins suggests a link between folding and brecciation (Marshall 2003; Marshal and Oliver 2004). The irregular margins of the clasts demonstrate that solution, as well as fracturing, has been a significant process. Together with the association between folding and brecciation, these observations are consistent with a relatively slow fragmentation process, in which chemical processes might have been important.

3. Type II Breccia

To the northwest of the outcrop, a very different type of breccia occurs. Fragments are generally more rounded, the breccia is matrix supported with a much higher proportion of matrix, and no continuity can be established from original bedding (this type of texture has also been described as "milled") These features are typical of type II breccias, which are commonly found in discrete veins that cross-cut the host rock. A spectacular example of a metre-sized block, detached from the adjacent intact Corella formation, can be seen near the W margin of the outcrop. This block itself is fractured at its ends and these fragments have been rotated.

Fig. 32. Typical Type II breccia: Roxmere waterhole.

Type II brecciation Mechanisms

The features of type II breccias at Roxmere waterhole and elsewhere suggest greater clast transport and rotation, possibly as a fluidised mass in a much higher energy environment. In other outcrops, fragments with dimensions of 10s of m can be inferred to have been transported at least several kilometres, implying very rapid fluid velocities (Oliver et al. submitted). High pressure fluids could have been derived from intrusive granites and gabbros (cf Butchers Creek), possibly due to explosive CO_2 release on mixing of mafic and felsic phases.

4. Albite Veins

Spectacular albite veins occur in places across the outcrop, showing excellent alteration selvedges.

Stop 5.2. "Cloncurry Fault" – breccias, schists, amphibolites

Drive down the track on the western side of the Snake Creek Anticline, to a creek crossing about 14 km from Roxmere Station. The fault is probably not the Cloncurry Fault but part of a NNE-trending zone that displaces the latter. Upstream we examine small bodies of breccia emplaced into the Soldiers Cap Group, amphibolite showing the typical moderately south-plunging mineral elongation, an F_4 fold in amphibolite, and a garnet-bearing schist showing crenulations and quartz boudins with shear sense indicators. The garnet grains at this location show complex spiral inclusion trails, interpreted by Sayab (2005) to be related the D_1 (~NS) shortening events (FIA, Foliation Intersection Axis of 125°- Fig. 33). The garnet in one sample contains chlorite and plagioclase inclusions, and Thermocalc modelling gave a core composition of 5-6 kbar, providing some of the earliest evidence that the P-T-t paths for rocks of the Snake Creek Anticline are in part within the medium pressure field.

The breccia immediately west of the fault is polymictic and poorly sorted, with most clasts derived from the Corella Formation, but with clasts of schist, quartzite, amphibolite and, more rarely, granite. Note that the foliations preserved in some clasts implies breccia formation after D_2, which is consistent with the association with ~1520-1530 Ma granites of the Williams Batholith. The Corella clasts are dominantly calcsilicates (replaced by mainly haematite-stained albite) and some marble, the matrix mineral assemblages including amphiboles and magnetite along with albite.

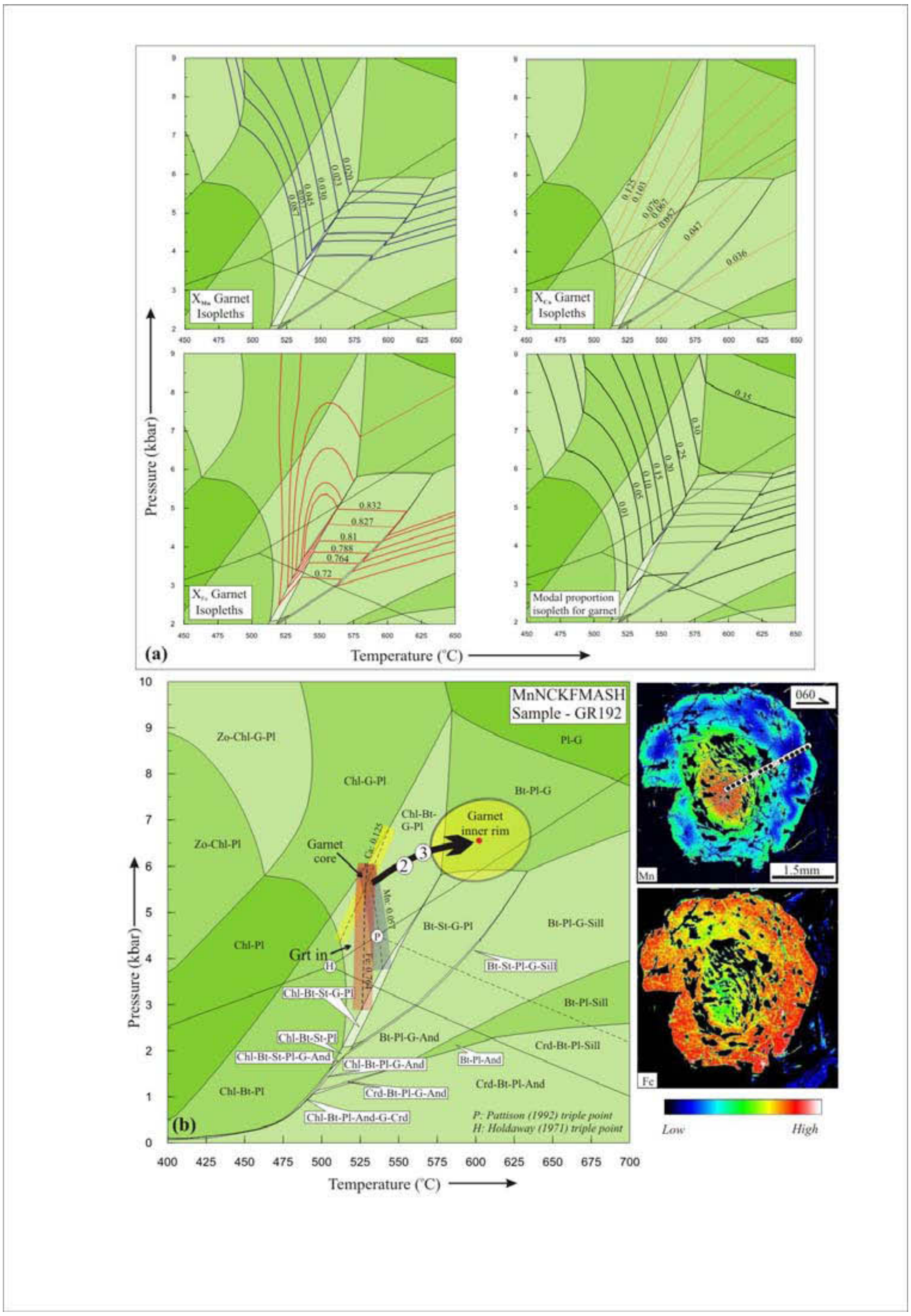

Figure 33. X-ray maps and Thermocalc pseudosection of a garnet schist sample, stop 5.2, from Sayab (2005). Note that the pressure for the core is 5-6 kbar.

The Cloncurry Fault

The Cloncurry fault is one of the most striking structures on the geological map of the Eastern Fold Belt. It is an ~ 200 km long, NNW trending structure comprising partly discontinuous fault segments up to 50 km long. The Mt Isa seismic profile has been interpreted to show the Cloncurry fault dipping moderately to the east (e.g. Goleby et al. 1998), although reprocessing of the seismic data permits an interpretation in which the fault is sub-vertical. The Northern part of the Cloncurry fault defines the boundary between Cover Sequence 2 (CS2; the Corella and Doherty Formations to the W) and Cover Sequence 3 (the Soldier's Cap group to the E) in the Eastern Fold belt. The Cloncurry fault also partly bounds some 1550-1500 Ma granites of the Williams-Naraku batholith (The Mt Angelay granite). Metamorphic grades increase to the east across the fault.

Along most of its length, the actual fault is not exposed, but in the central portion, a segment that trends slightly anticlockwise of the average trend has a prominent quartz infill, gouge, breccia and veining similar to the features of the Fountain Range and Spillway faults.

The southern part of the fault coincides with one of the largest geophysical lineaments in the Eastern Fold Belt, known as the "Cloncurry worm", which in general terms separates higher susceptibility rocks of CS2 from the generally low susceptibility rocks of the Soldiers Cap group. An increase in Bouger gravity anomaly to the east of the lineament could be due to a shallowing of the denser basement. The Cloncurry lineament progressively diverges from the Cloncurry fault to the North, and at the latitude of Snake Creek, the lineament is 10 -20 km east of the fault.

The fault appears to have had a long history involving reactivation. A possible influence on sedimentation is permitted by the extensive coincidence of the fault with the Soldier's Cap/Corella formation boundary, combined with the restriction of the Soldier's Cap group to the E of the fault throughout its northern portion. However, the higher metamorphic grade of the E side (sillimanite zone versus greenschist facies assemblages of ~500°C in unmetasomatized Corella Formation) suggests a subsequent reverse component of movement. The fault may have played some role in the intrusion of parts of the Williams batholith, and has been associated with extensive hydrothermal alteration (e.g. de Jong and Williams 1995). Post-Saxby granite sinistral movement is evidenced by the displacement of that granite and an E-W dolerite of uncertain age. A Phanerozoic movement history has been suggested by Mark et al. (2004) on the basis of oxygen isotopic signatures of quartz. Post Jurassic movement has certainly occurred along the fault: Mesozoic mesas are cut and displaced vertically by the fault by approximately 100 m.

Stop 5.3. Macroscopic F_2 fold, albitites and biotite-staurolite metasomatic rocks

From the crossing of Snake Creek about 15 km from Roxmere Station, walk east for about 1 km, passing through a quartzite ridge at the base of the Mount Guide Quartzite and the uppermost carbonaceous metasedimentary rocks of the Llewellyn Creek Formation. At this location we will examine graded metapsammite beds (turbidites, Bouma A) indicating overturning, muscovite schists with staurolite, garnet and andalusite pseudomorphed by muscovite, albitites, and biotite-staurolite-garnet metasomatic rocks adjacent to albitites (Figs. 34, 35).

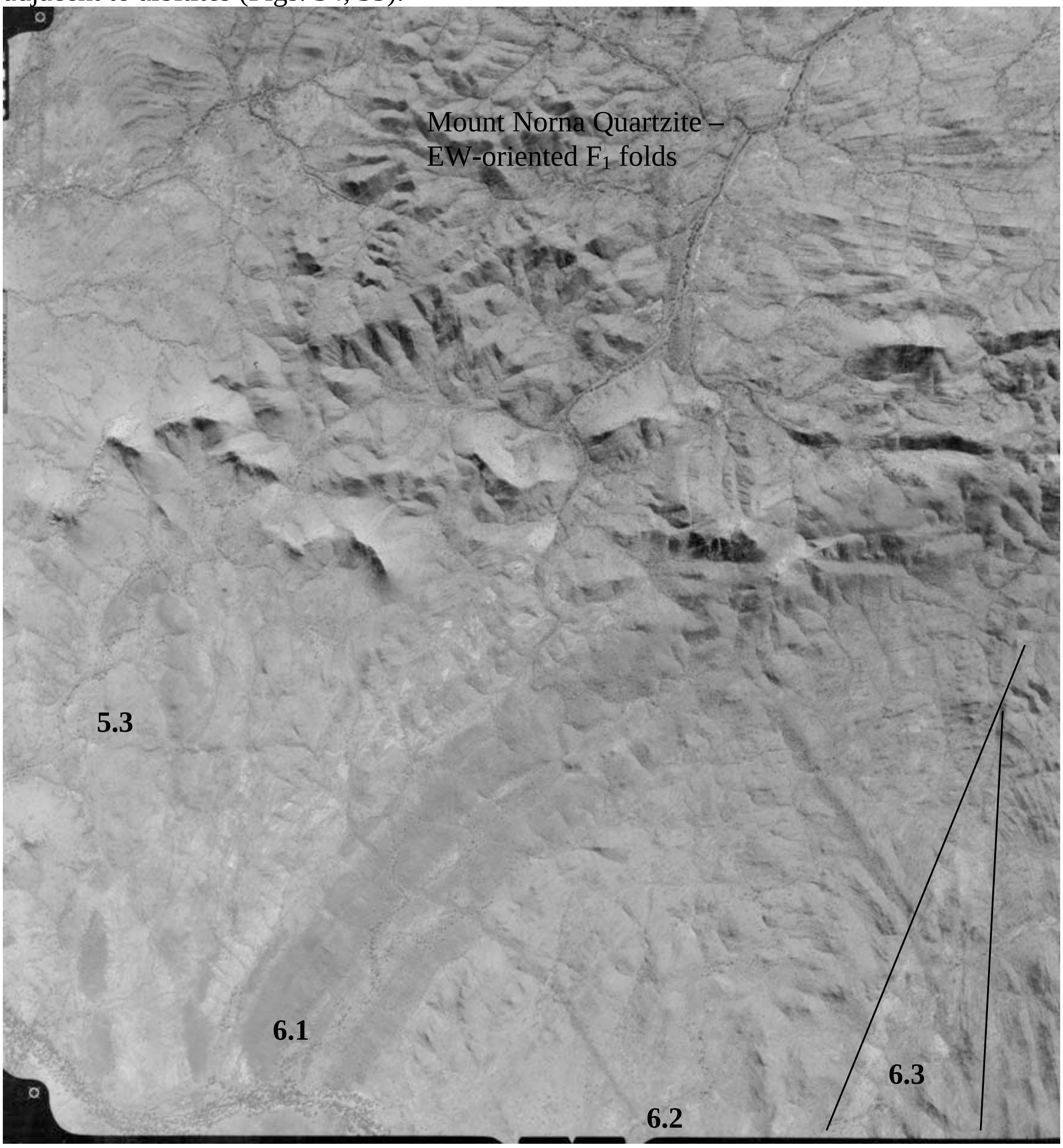

Figure 34. Airphoto of the NW of the Snake Creek Anticline. The width is about 5 km. Note the isoclinal fold partly outlined by the darker metadolerite at stop 5.3, with the main sill complex of metabasics and tonalite (lighter coloured) at 6.1, the two faults shown as black lines near 6.3, and "syn-D_2" metadolerite dykes near 6.2 and 6.3.

The locality here is in the hinge of a complex macroscopic F_2 anticline outlined by amphibolitized metadolerite that is connected to the main sill of metadolerite, metagabbro and tonalite (Figs. 34, 35). It is proposed that fold resulted from the ductility contrast between the metadolerite and the now core of metasedimentary rocks.

At about 500 m to the SSE we will examine a mesoscopic F_2 fold, a set of en echelon quartz veins with magnetite, pyrite and gedrite alteration of the adjacent metadolerite, and a zone of highly strained gedrite-albite-garnet rocks that have replaced schists between two layers of metadolerite.

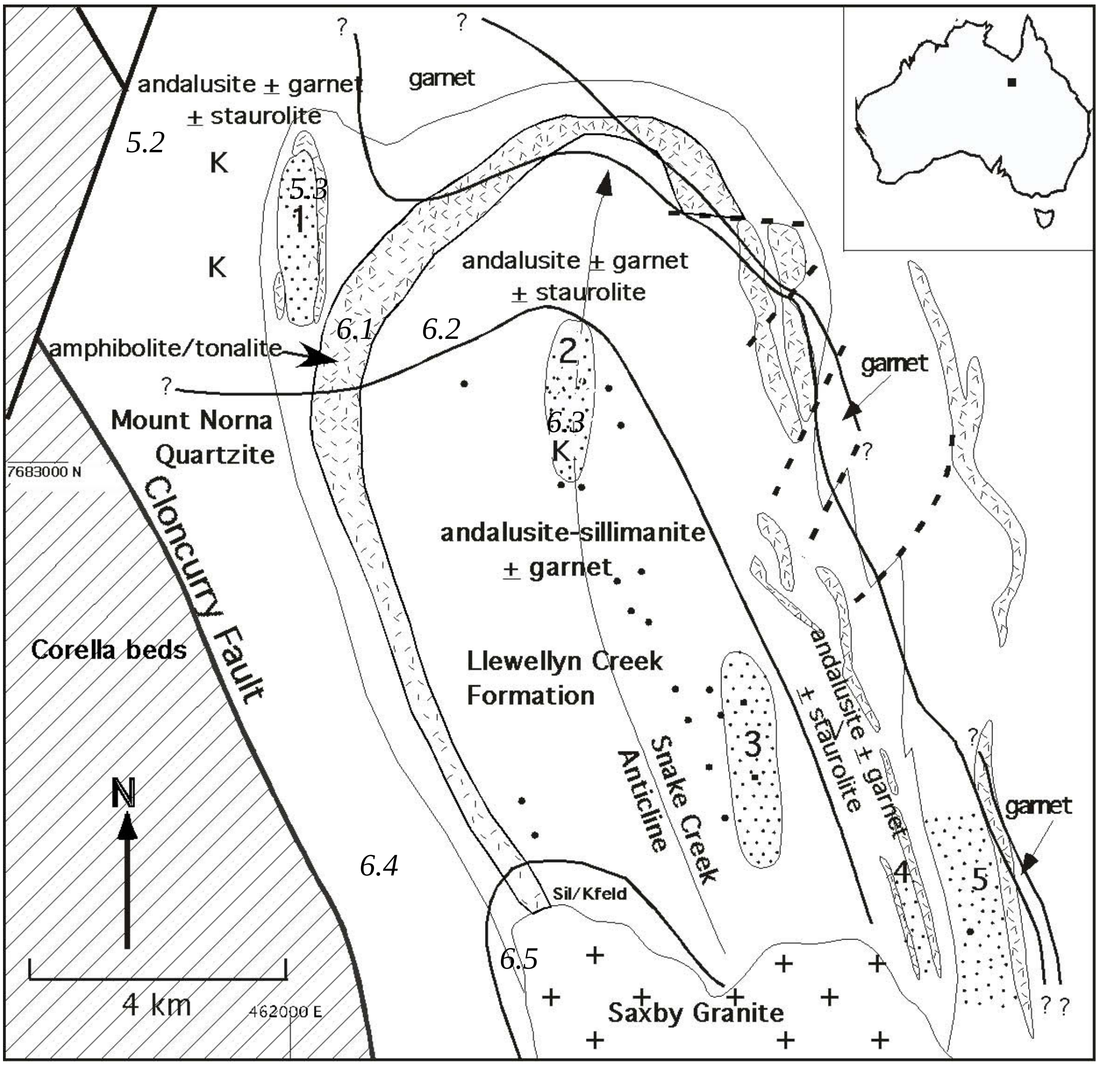

Figure 35. Isograd map of the Snake Creek Anticline. Stippled areas 1-5 represent more intense early albitization; larger dots, cordierite; K, kyanite. The isograds are composite, $D_1$to D_5, except for the sillimanite/Kfeldspar zone which formed during the emplacement of the Saxby Granite during D_5. Stops 5.2 to 6.5 are shown in italics.

DAY 6. SNAKE CREEK ANTICLINE – STRUCTURE, METAMORPHISM, METASOMATISM; BRECCIA DYKE; MINGLED GRANITE AND DOLERITE

Structural geology of the Snake Creek Anticline

Despite all the work done on this key area in the Eastern Fold Belt, many aspects of the structure remain controversial and some problems are still unresolved. Most workers agree that NS shortening (D_1) was followed by essentially EW shortening (D_2 and most subsequent events). There is dispute concerning the number of events (e.g., Loosveld, 1989, discusses one D_1 event, Lewthwaite, 2000, proposed two, and Sayab, 2005, at least three), and the overall significance of post-D_2 events, especially D_3 which produced shallowly-dipping structures. However, the main area of disagreement concerns the existence of thin-skinned deformation in D_2, in particular the formation of the Snake Creek Anticline an F_2 westward verging nappe, with the commonly steep S_2 explained by subsequent folding (O'Dea et al., 1997; Giles & MacCready, 1997). In contrast, a number of researchers from JCU argue that the Anticline formed as a steep structure and that overturning in some areas is the result of D_3 (Holmes, 1991; New, 1993; Lewthwaite, 2000). The two competing models are summarized in Figure 36.

The Snake Creek Anticline, plus the EW-trending F_1 folds to the north, is shown in Figure 37. Recent work, however, has demonstrated that the northern part of the axial trace of the Snake Creek Anticline does not swing to the east, as indicated on this figure. Figure 38, also from Lewthwaite (2000), shows bedding and younging over a large part of the anticline. The western limb is predominantly overturned, and whereas the northern part of the fold (which plunges north) is not overturned and is therefore an antiformal anticline, the southern part is a south-plunging synformal anticline (Figure 39). Most of the eastern limb is right-way up. The essential paradox of the Snake Creek Anticline is that the change from antiformal to synformal geometry is not accompanied by any map-scale evidence for refolding or recognised discontinuity, despite the evidence for a D1 fabric. Can this geometry be achieved by a single progressive deformation?

Metamorphism

Rubenach & Barker (1998) and Rubenach & Lewthwaite (2002) demonstrated multiple growth episodes from D_1 through to D_5 (note that the latter authors refer to D_2 as D_3). The peak was placed at syn-D_2, but now we would place it from late D_2 to syn-D_3. Work by Sayab (2005) demonstrated that the necessary use of oriented thin sections and of FIA's (foliation intersection axes) in porphyroblasts as the multiple growth events and widespread reactivation of foliations in younger events otherwise may lead to confusion and incorrect identification of growth events. The suggested P-T-t paths of Rubenach & Barker (1998) and Rubenach & Lewthwaite (2002), essentially anticlockwise with isobaric heating and cooling events, has been now shown, with detailed modelling using Thermocalc pseudosections, to be simplistic, and the overall path is clockwise (Sayab, 2005; Rubenach, unpubl. pmd*CRC report). Critical microstructural observations include:

1. Early growth of cordierite, followed by andalusite (with or without garnet, staurolite, kyanite, sillimanite)
2. Early andalusite replaced by kyanite, in turn replaced by late andalusite
3. Multiple andalusite with later sillimanite
4. Early andalusite, later staurolite, in turn replaced by late andalusite
5. Early garnet with 5-6 kbar cores
6. Late cordierite and/or andalusite+Kfeldspar+sillimanite

Figure 40 shows a suggested composite P-T-t path for the Snake Creek Anticline based on the above observations and over 10 calculated pseudosections.

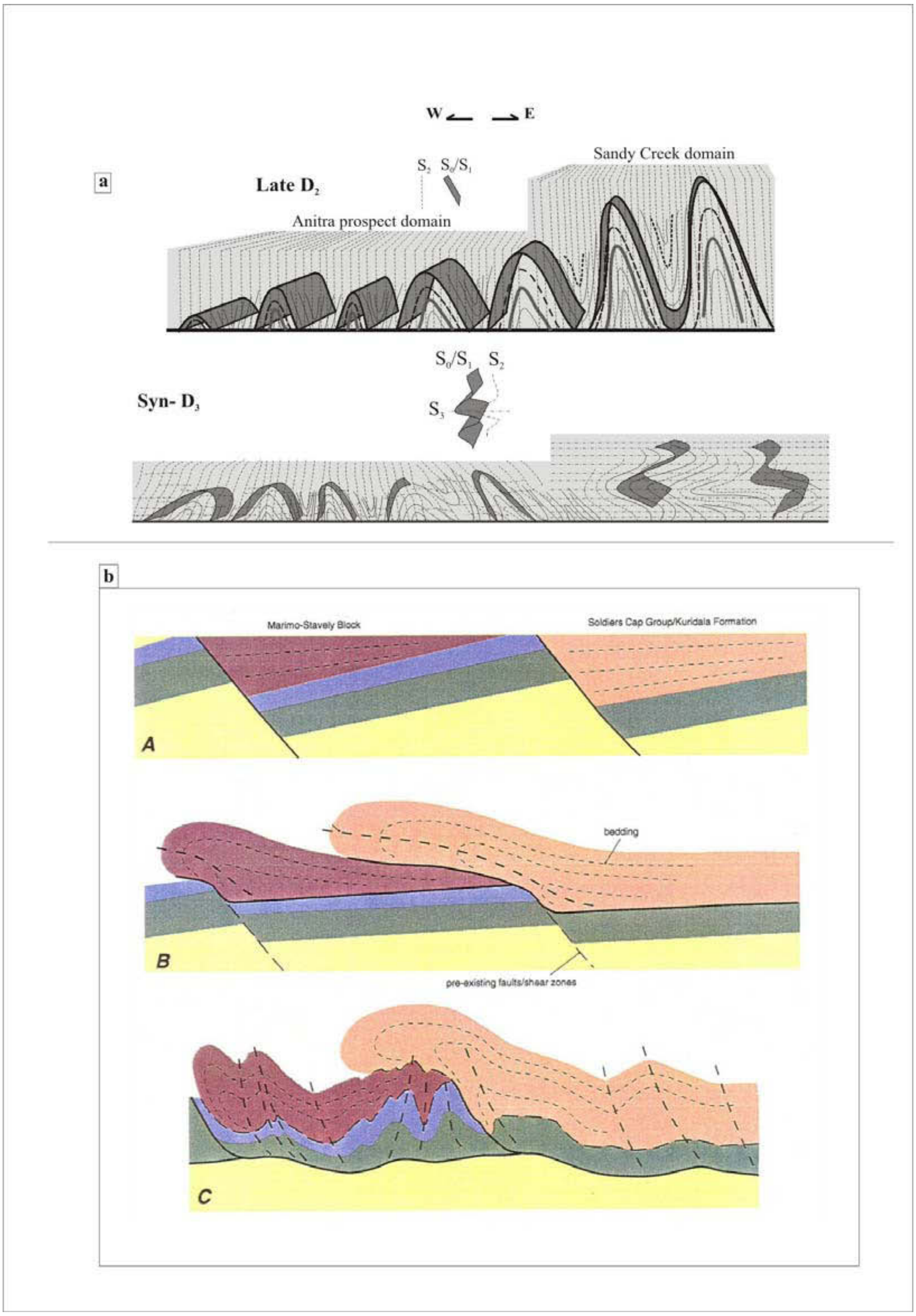

Figure 36. Contrasting structural models for the Eastern Fold Belt (from Sayab, 2005). (a) is based on detailed work by Sayab in the area north of Osborne, while (b) is essentially the Giles & MacCready(1997) model, the eastern nappe representing the Snake Creek Anticline.

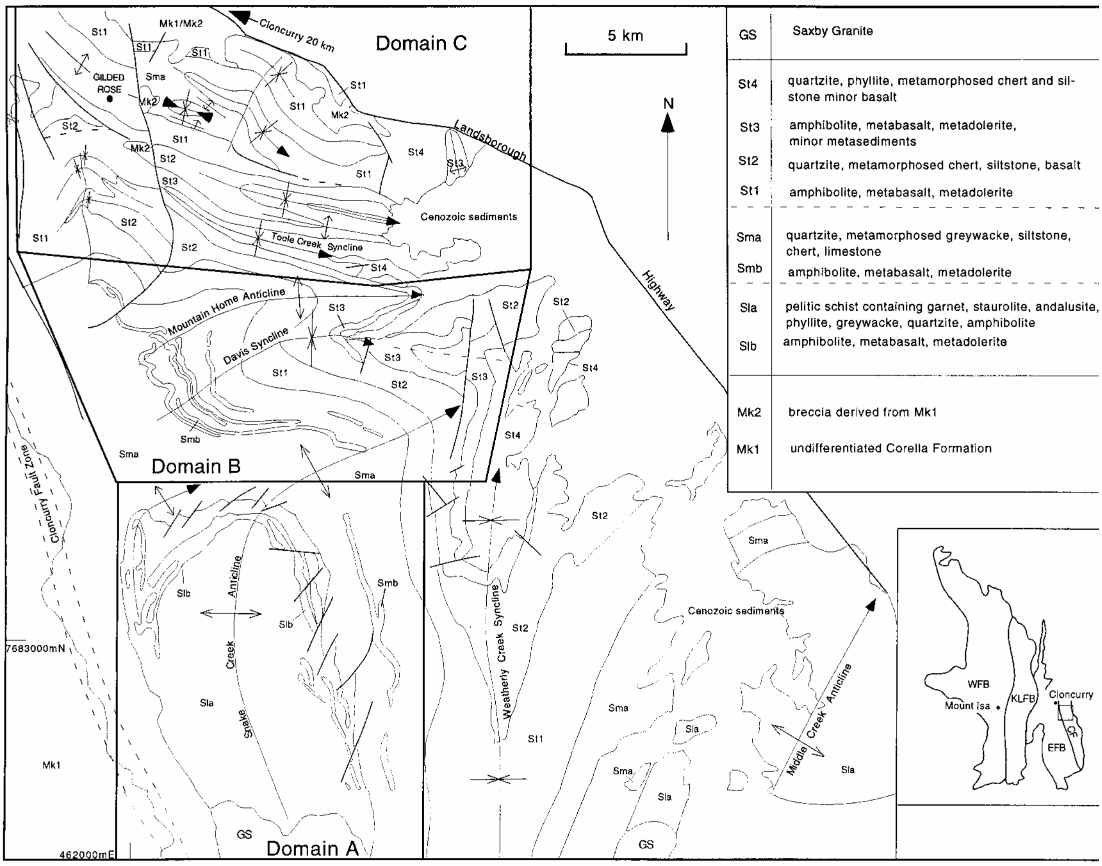

Figure 37, from Lewthwaite (2000). The EW axial traces are D_1structures and the NS axial traces D_2. The Snake Creek Anticline is now known not to swing eastwards in Domain B.

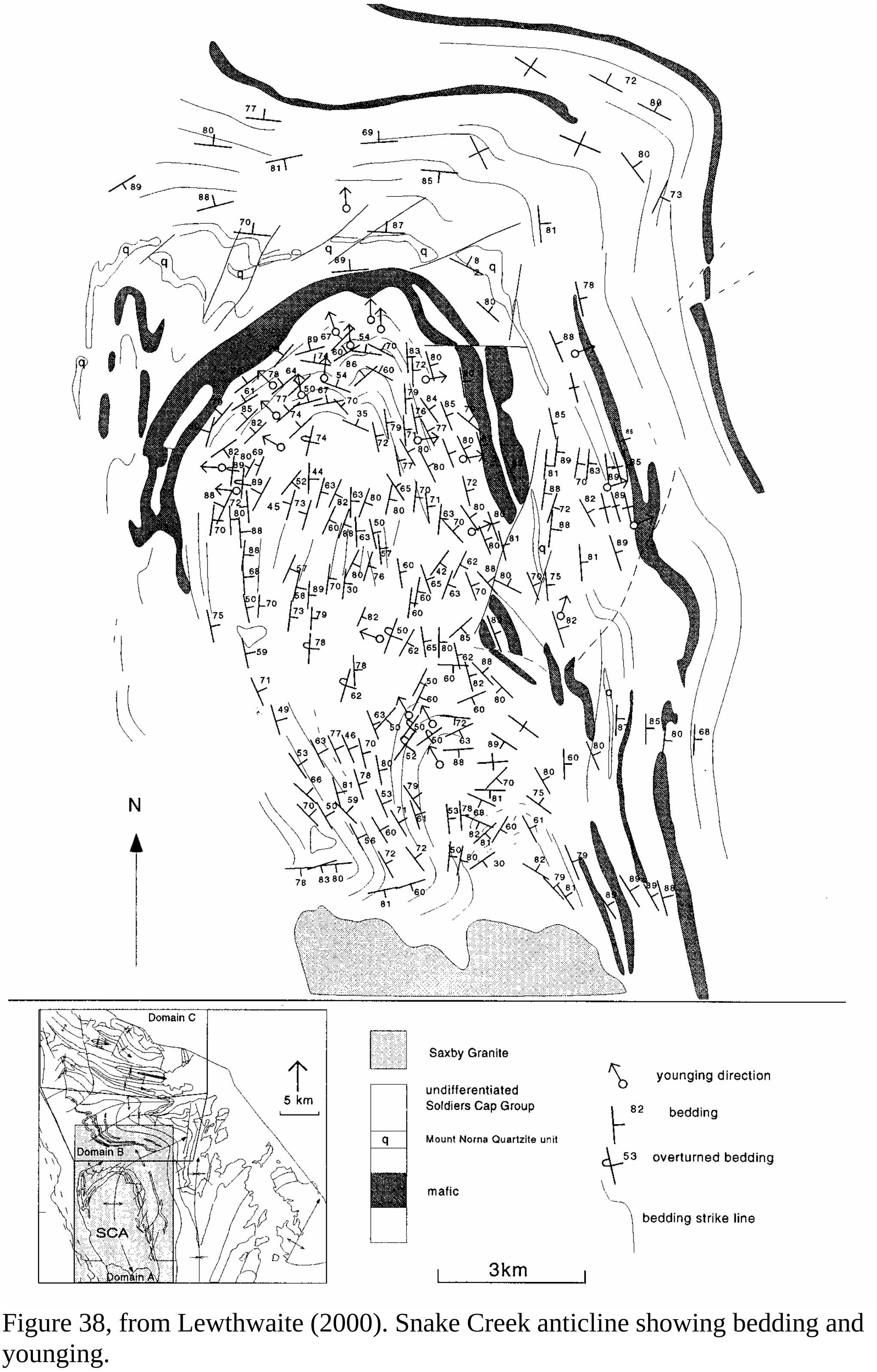

Figure 38, from Lewthwaite (2000). Snake Creek anticline showing bedding and younging.

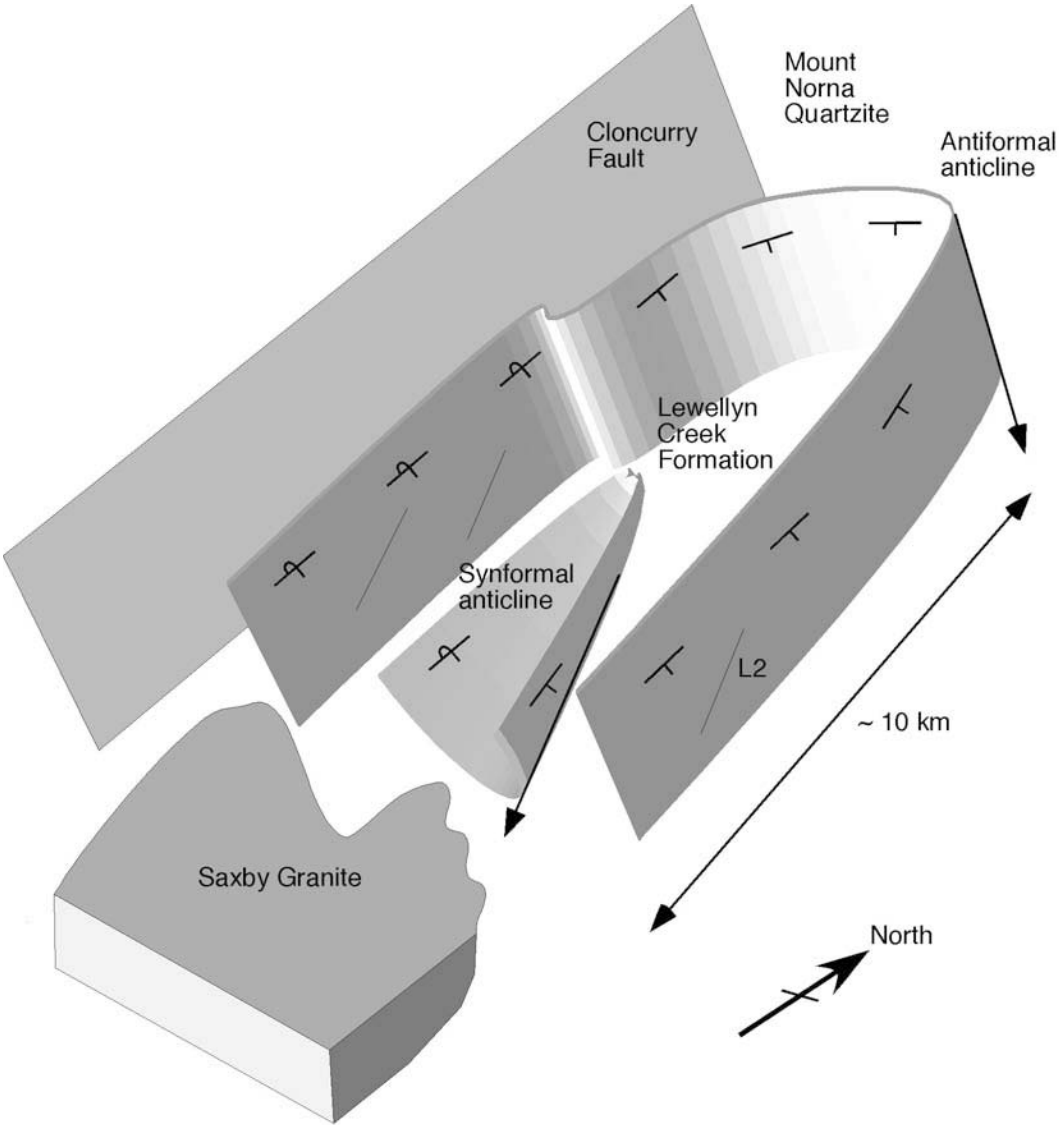

Figure 39. Oblique view of the Snake Creek Anticline, Cloncurry fault and Saxby granite

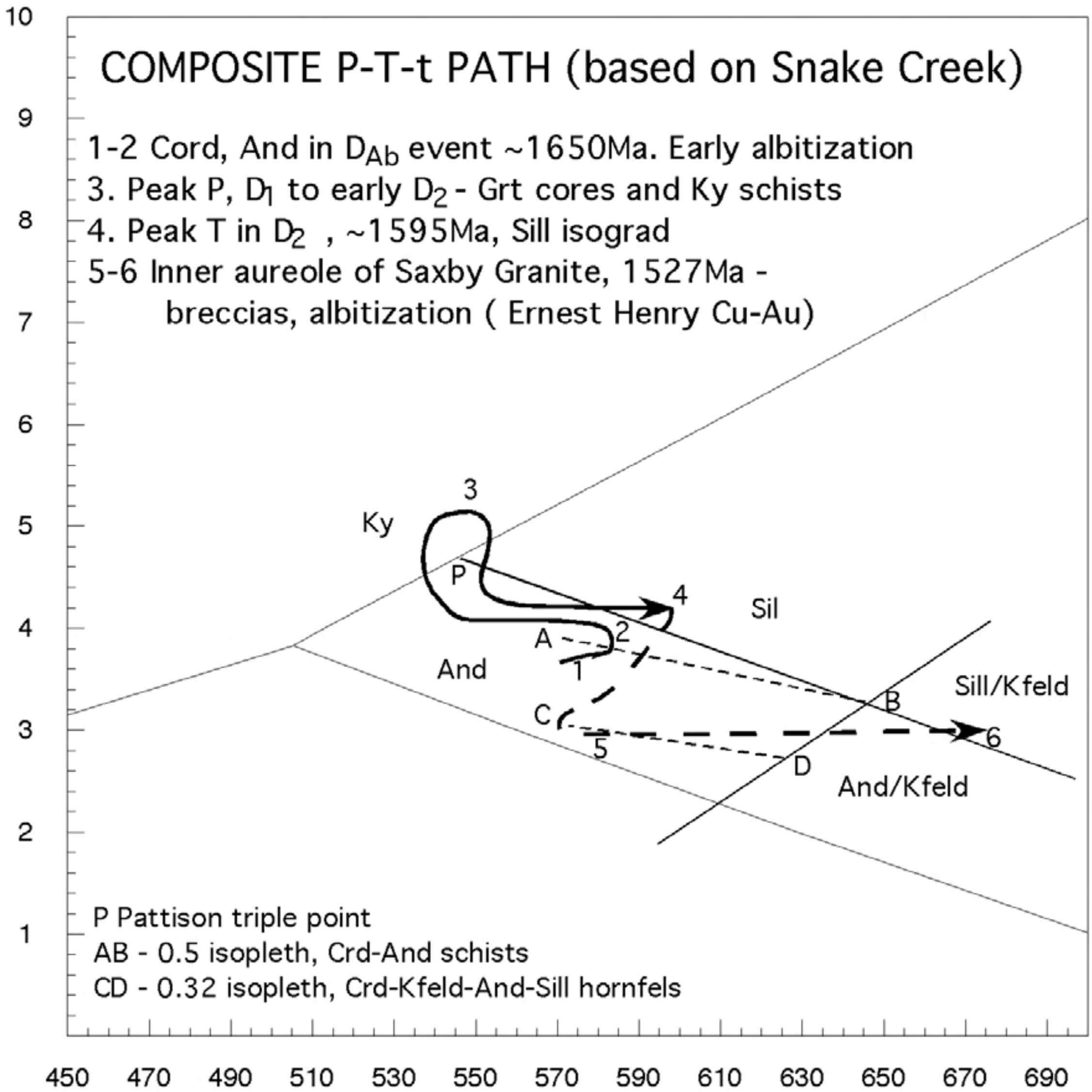

Figure 40. Composite P-T-t path. The solid line corresponds to rocks in the northern part of the snake Creek Anticline, at the sillimanite isograd. The dashed path refers to rocks in the aureoles of granites from the SW of the Anticline. The Pattison triple point is preferred over the Holdaway aluminosilicate triple point. The timing of the early cordierite growth is still uncertain. The isopleths are Mg/(Mg+Fe) for biotite that, along with andalusite, has replaced cordierite

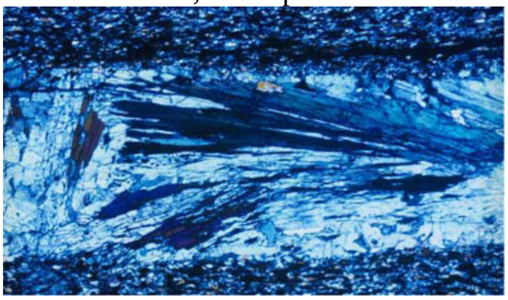

Figure 41. Schist with andalusite replaced by kyanite, in turn replaced by andalusite. Length 5.6 mm.

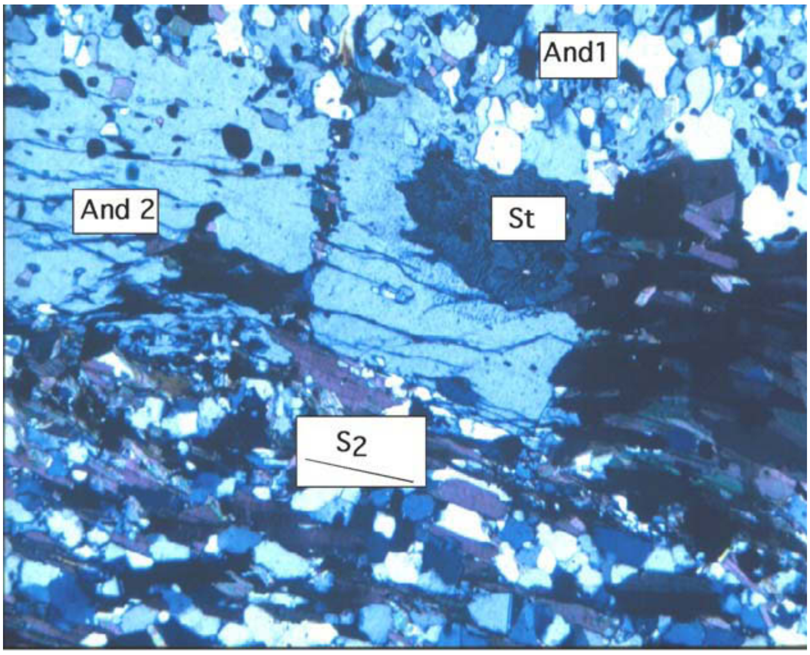

Figure 42. Schist in which andalusite 1 preserves a weak S_1, whereas andalusite 2 has overgrown S_2. Andalusite 2 has also largely replaced staurolite. Length 5.6 mm.

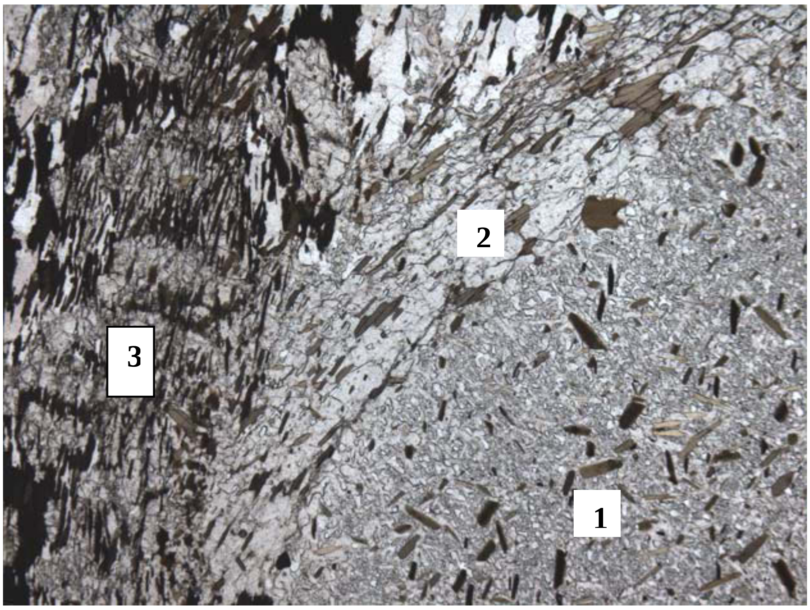

Figure 43. Three growth stages of andalusite are shown, with truncations between each stage. Length 5.6 mm.

Stop 6.1. Layered gabbro, amphibolite and tonalite
Continue past the second Snake Creek crossing east of stop 5.4 for about 3 km, past the prominent mesa of Davis Hill, to a track intersection. Turn east on this track, for about 3 km. We will examine an outcrop of layered gabbro (now replaced by amphibolite, but not foliated here). This is part of a gabbro-dolerite-tonalite sill complex. The tonalite, which locally mingles with gabbro and which outcrops nearby, intruded at 1686 Ma.

Stop 6.2. Bouma sequences in andalusite-garnet schists
Drive about 2km east from 6.1, walking about 100 m south to a creek. Here we will examine typical Llewellyn Creek Formation metapsammites and schists, the precursors of which were clearly turbidites with well-preserved Bouma sequences. The pelitic layers are muscovite schists with andalusite and garnet, the most common assemblage in the andalusite zone, contrasting with cordierite-andalusite schists associated with albitites at stop 6.3.

Stop 6.3. Cordierite schists, albitites, biotite-rich schists, metadolerite
A few hundred metres past 6.2 the track crosses a larger creek.
Several hundred metres along the track is a metadolerite dyke, one of a dyke swarm. Dykes of this generation are approximately parallel to the axial plane in the southern part of the Snake Creek anticline, but diverge northwards so that they are roughly normal to the strike of the bedding. A few patches of two pyroxene quartz dolerite are preserved, but most have been converted to amphibolite, with either igneous texture preservation or foliated at the margins or throughout. Walking further east along the creek we will pass typical andalusite schists and metapsammitic rocks, with layers of albitite increasing in abundance. Initially albitization is restricted to the metapsammites, with muscovite replaced by albite. In place of garnet most of the schists associated with albitites grew early cordierite (now replaced by biotite and andalusite). Cordierite pseudomorphs and andalusite are quite abundant in some schists, especially metasomatic muscovite-free biotite-rich schists.
We will traverse northwards up a creek that intersects the main creek about 800 m east of the track. We are approximately in the centre of albitite area 2 (Figure35), where pseudomorphed cordierite, albitites and adjacent biotite-rich schists are now quite abundant. We will examine outcrops also containing visible kyanite. In some samples, cordierite has been replaced by biotite, kyanite and andalusite (with less common staurolite and fibrolite). Tourmaline is also fairly common, replacing cordierite and occurring along fractures.
Albitite area 2 is now known to be bounded by two faults (Figure 34). The easternmost fault is marked by mylonitic albitite and siliceous rocks, with a steep foliation and steeply plunging lineation. The major fold vergence reverses across each of the faults, with the eastern limbs of mesoscopic folds overturned and the bedding and foliation generally shallower relative to those outside the fault block. Metadolerite dykes, which possess the “S_2” foliation, are not displaced by the faults, an observation difficult to explain unless this foliation is really S_4.
We will examine a location about 500 m north along the creek where a major albitite vein occupies a shear zone in the hinge of a mesoscopic fold (Figure 42). The bedding cannot

be matched across the shear zone. The fine-grained albite in the shear zone has replaced metasedimentary rocks, although many of the thinner associated albite veins are probably formed by infill. Metapsammitic rocks adjacent to the main vein have been albitized, whereas adjacent schists have been replaced by metasomatic biotite-rich muscovite-free schists that commonly contain abundant cordierite replaced by biotite and andalusite. A model is included for the origin of these metasomatic rocks, and to explain the large-scale zone of low (7-10 ‰) oxygen isotopes in both metasomatized and non-metasomatic rocks alike in and around the albitite areas (Figure 44). It is now thought that the infiltrating fluids are more likely to be mantle derived rather than being sourced from the granites or the Corella Formation.

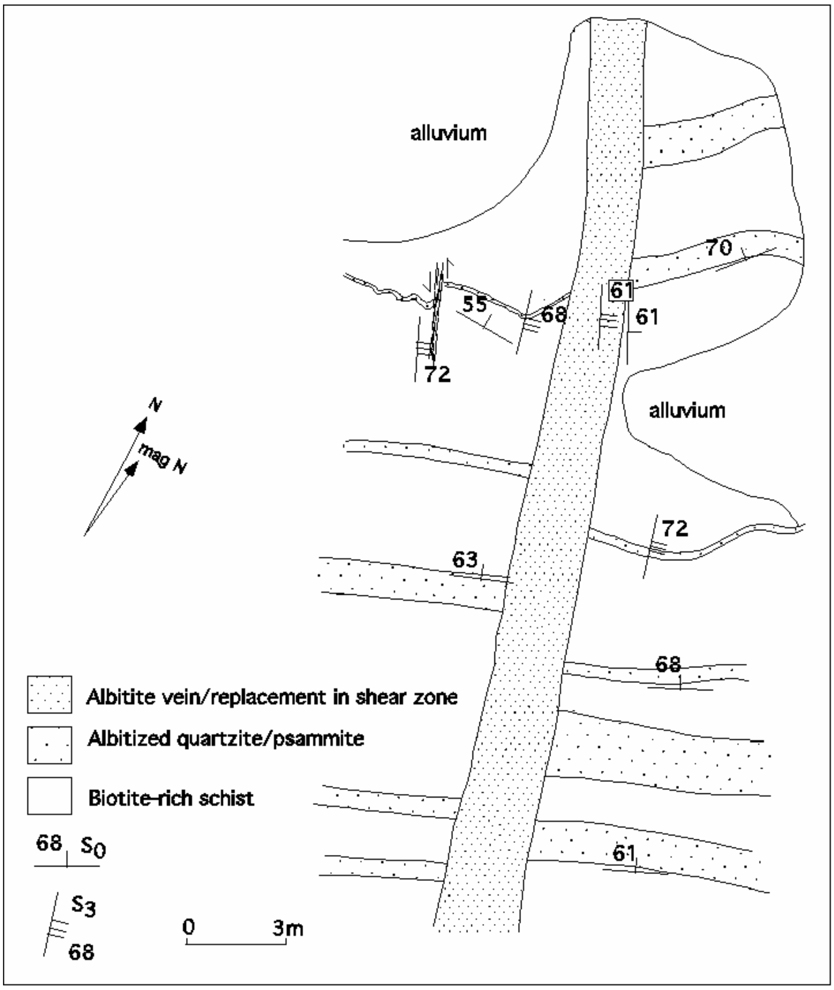

Figure 44, from Rubenach & Lewthwaite (2002). Replacement albitite vein occupying a shear zone in the hinge of a mesoscopic fold, albitite area 2. In this guidebook the main foliation is referred to as S_2 rather than S_3.

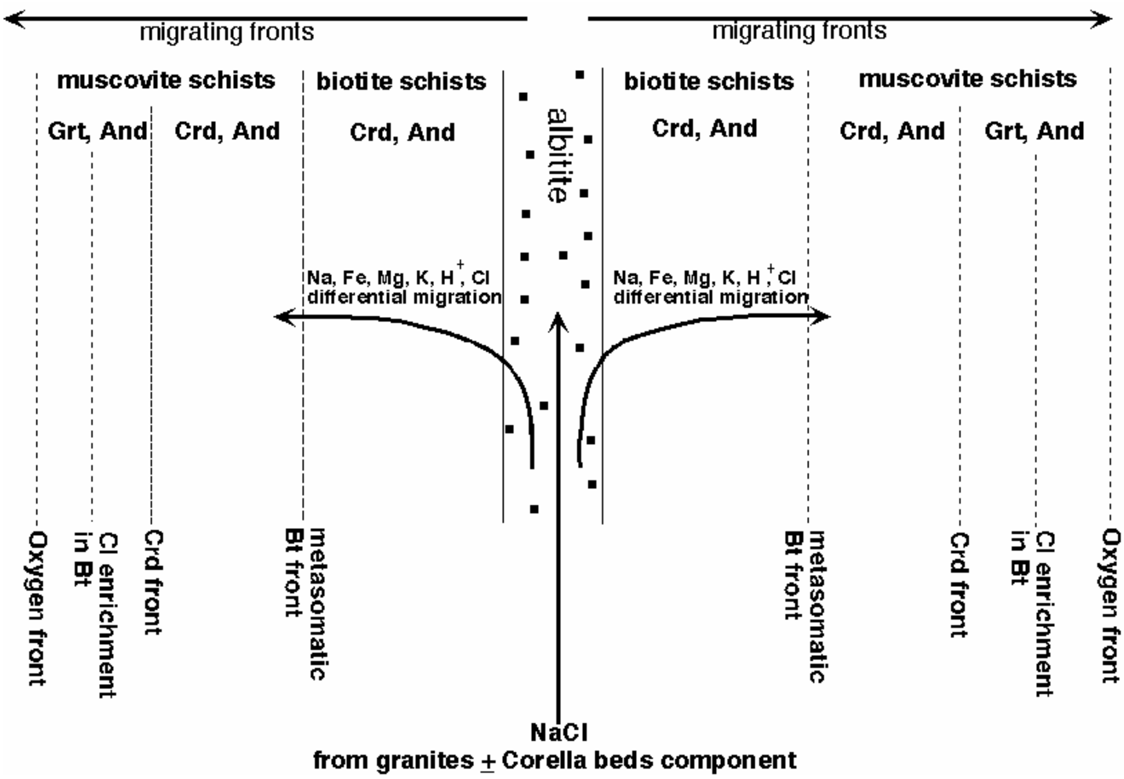

Figure 45, from Rubenach & Lewthwaite (2002) and Rubenach (2005). The source of the fluids is now thought to be of direct mantle origin rather than from granites and Corella Formation. The diagram is not to scale, as the biotite front may be only a few metres from larger veins while the oxygen front is kilometres.

Chlorine enrichment occurs in biotite from biotite-rich schists occurring in most albitite-rich areas, and in a particular sample biotite in each andalusite growth zone and in the matrix form distinct populations on Cl versus Mg/(Mg+Fe) plots (Rubenach, 2005).

Stop 6.4. Breccia dyke

Return to the main track, driving about 6 km south. We will walk through a gap in quartzite ridges about 200 m west of the road.

Besides forming steep pipes, breccia bodies also have intruded schists of the Soldiers Cap Group as “dykes”, and occur as carapaces around small bodies (length or diameter 10^2 - 10^3 m) of granite that have intruded the Soldiers Cap Formation immediately east of the Cloncurry Fault. The dyke at this locality starts at the gap, extends for about 800 m SW, the turns south and west to eventually connect with a breccia carapace around a granite (Figure 46). The dyke margins are sharp and approximately parallel to the string S2 foliation in the adjacent schists. We will examine pegmatite bodies that indicate a dextral displacement at the eastern end, breccia clasts (mainly albitized calcsilicate rocks, but include granite, hybridised granite, pegmatite and gabbro), the metamorphic and metasomatic assemblages (which include albite, calcite, pyroxene, several types of amphibole, biotite, scapolite and magnetite), and an associated quartz-haematite body. Some albitite veins, generally less than 20 cm thick, extend up to 100m from the breccia dyke. In contrast to the older albitites at stop 6.3, the breccias and albitites at 6.4 are associated with the Saxby Granite, bodies of which have been dated in the range 1520-1530 Ma. The dyke is 10 – 20 m wide and one calcsilicate clast occupies virtually the whole width of the dyke. The emplacement of such clasts poses obvious geometrical problems, and the transport of clasts in other instances that have dimensions of 10s of m also place severe constraints on the brecciation transport mechanisms.

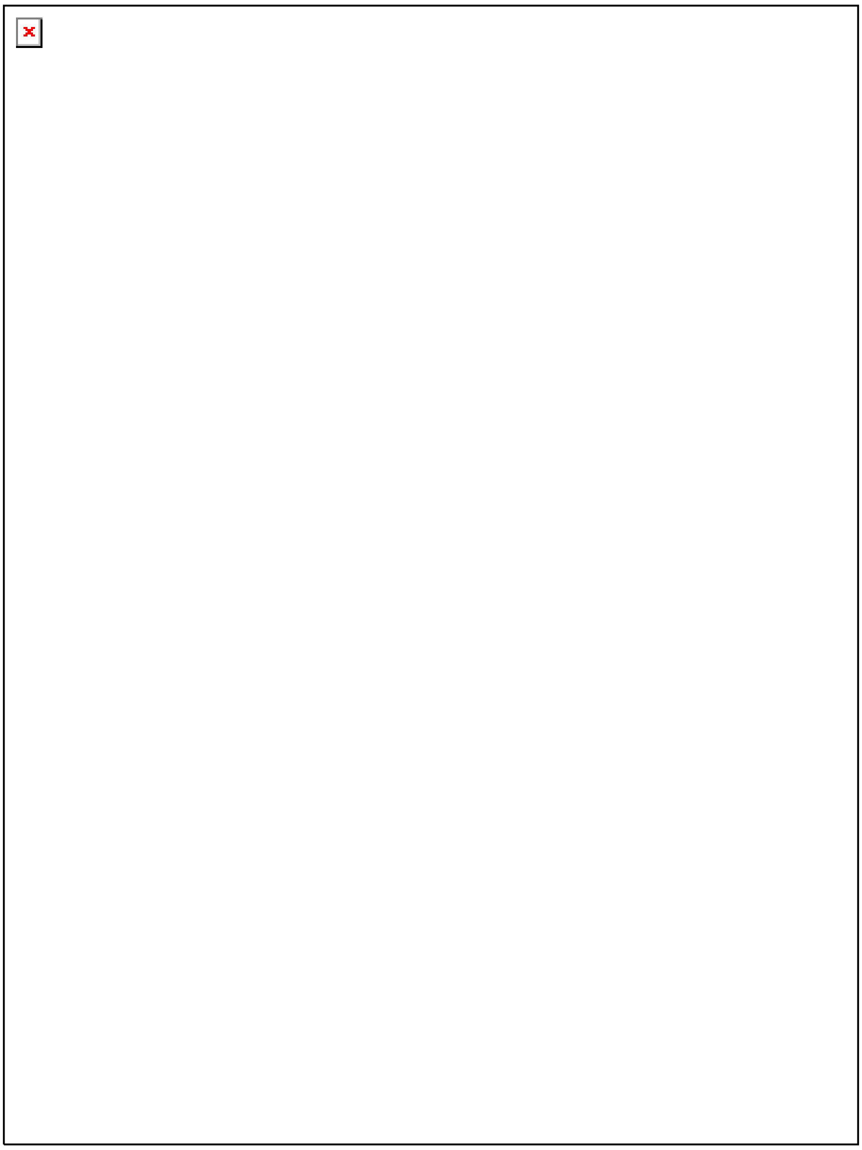

Figure 46, from Oliver et al. submitted. Breccias and granites south of Cloncurry. Stop 6.4 corresponds to c, while stop 6.5 is a few km south of c.

Stop 6.5.
From 6.4 we will drive another few km south to a gate. Just south of the gate we will examine migmatitic sillimanite/Kfeldspar gneiss related to the nearby Saxby Granite, late folds in the gneiss, and dolerite and granite mixing.

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Appendix 5a: Structural Data and Field Observations

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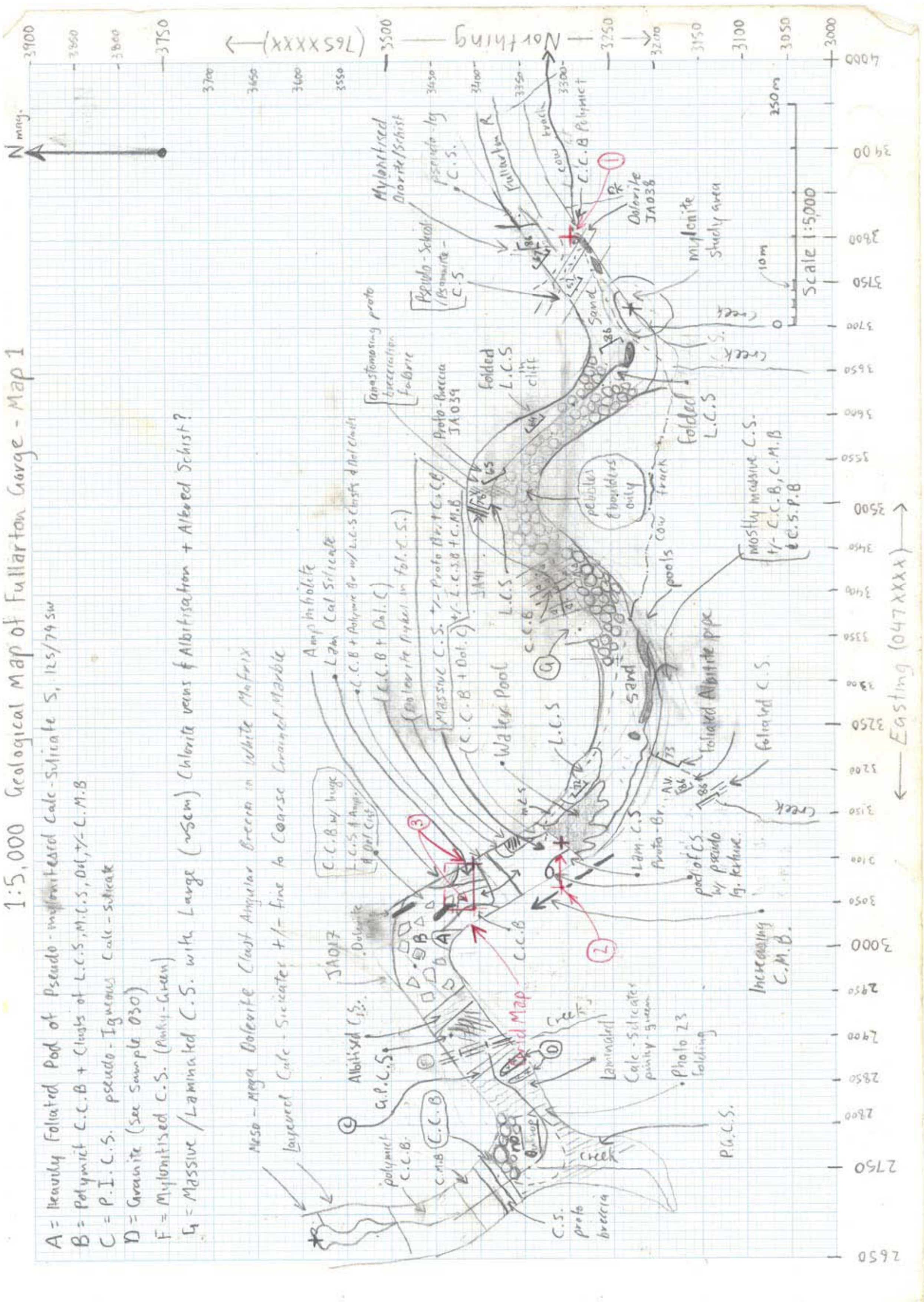
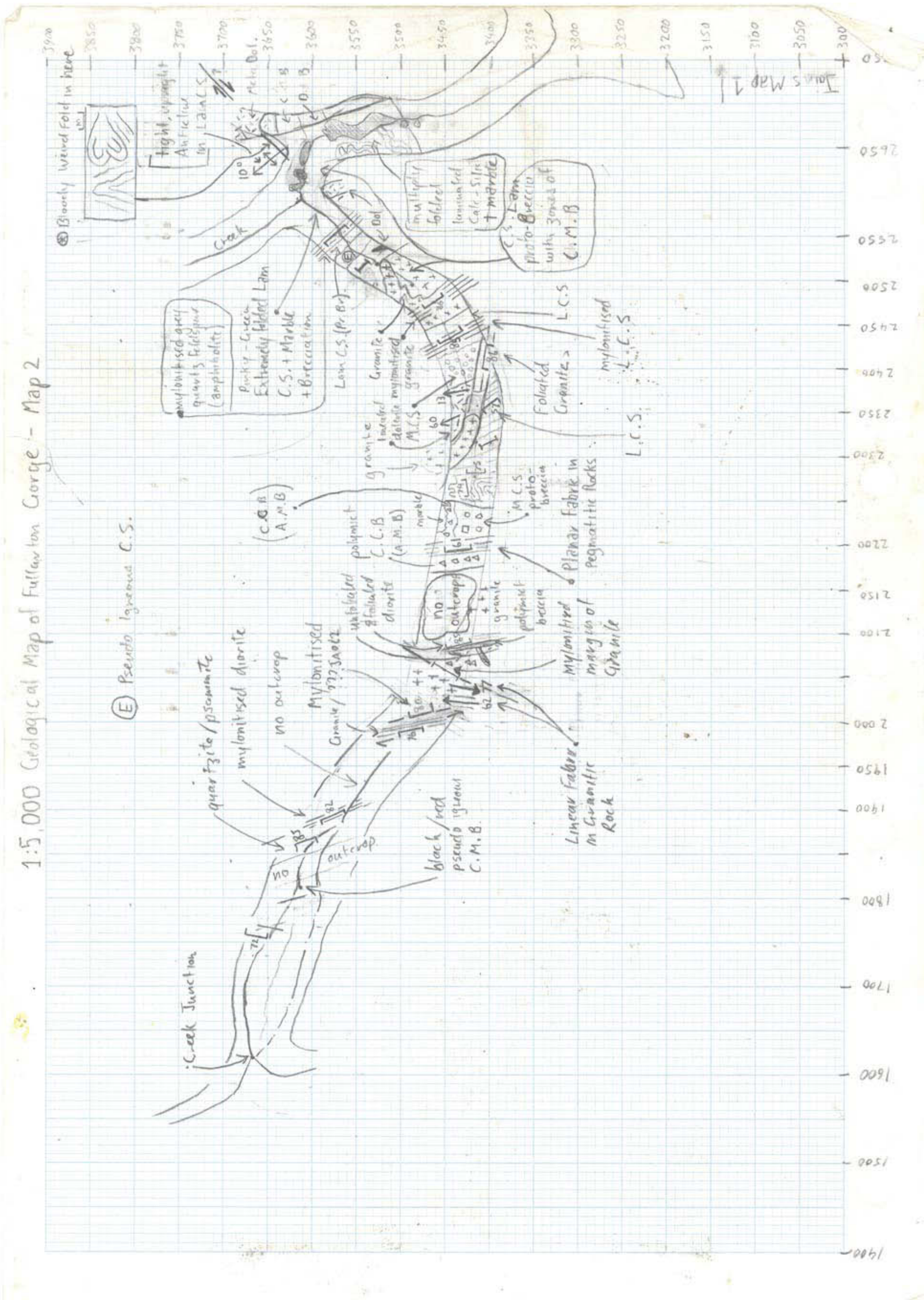
Appendix 5b: Field Maps

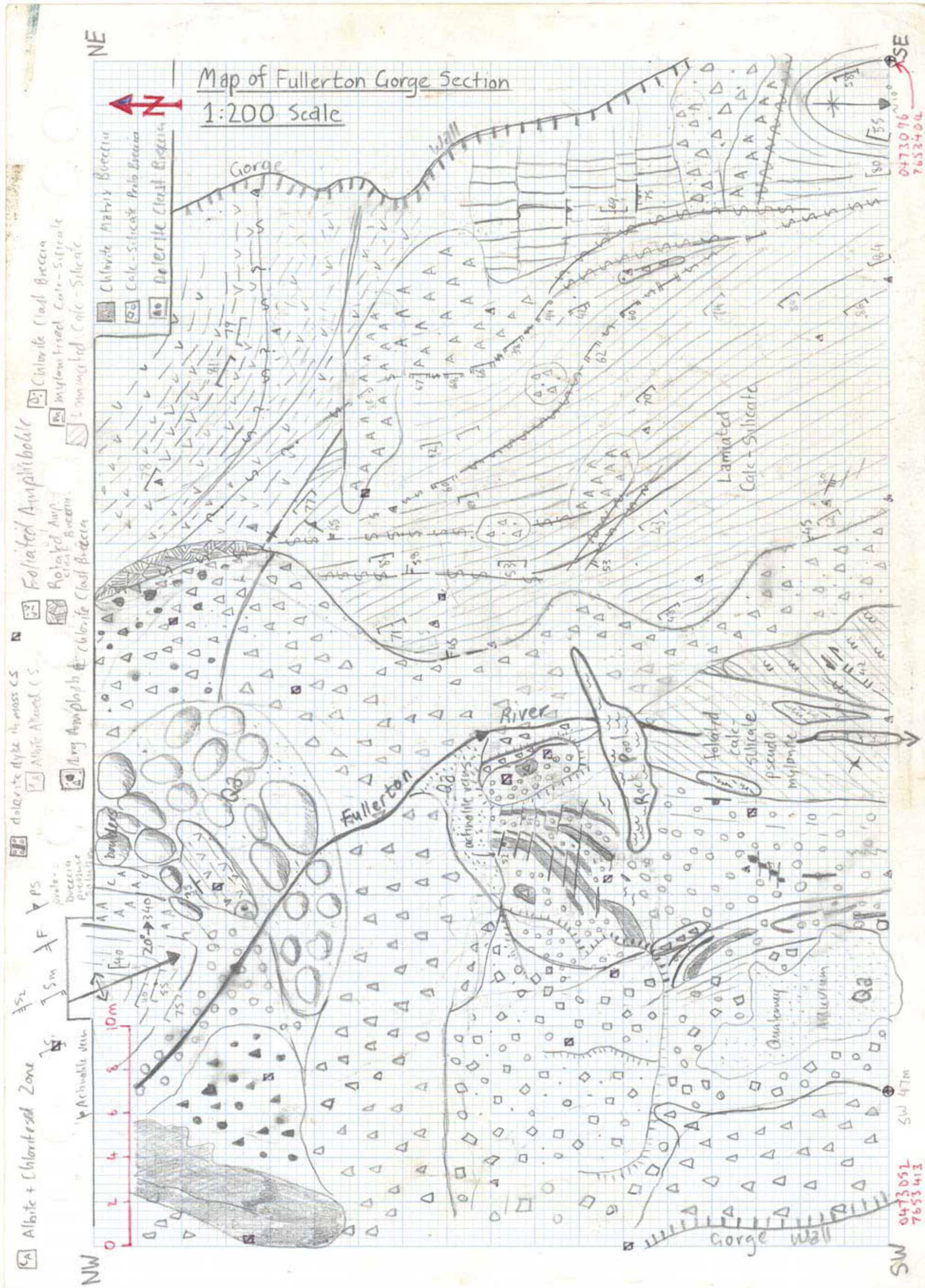

1:5,000 Geological Map of Fullarton Gorge - Map 1
A = Heavily Foliated Pod of Pseudo-mylonitised Calc-Silicate S, 125/74 SW
B = Polymict C.C.B + Clasts of L.C.S, M.C.S, Dol, +/- C.M.B
C = P.I.C.S. pseudo-Igneous Calc-Silicate
D = Granite (See Sample 030)
F = Mylonitised C.S. (Pinky-Green)
G = Massive / Laminated C.S. with Large (~5cm) Chlorite veins & Albitisation + Altered Schist?
N mag.
Northing
Easting
Scale 1:5,000
250m
Mylonitised Diorite/Schist
Folded L.C.S
Proto-Breccia
Water Pool
pools
sand
creek
cow track
Foliated Albitite pipe
Foliated C.S.
Mostly massive C.S.
pebbles & boulders only
Layered Calc-Silicates +/- fine to Coarse Grained Marble
Meso - mega Dolerite Clast Angular Breccia in White Matrix
Amphibolite
Laminated Calc-Silicates pinky green
Increasing C.M.B.
Photo 23 folding
Grid Map
mylonite study area
Dolerite JA038
C.S. proto breccia
P.G.C.S.

Appendices

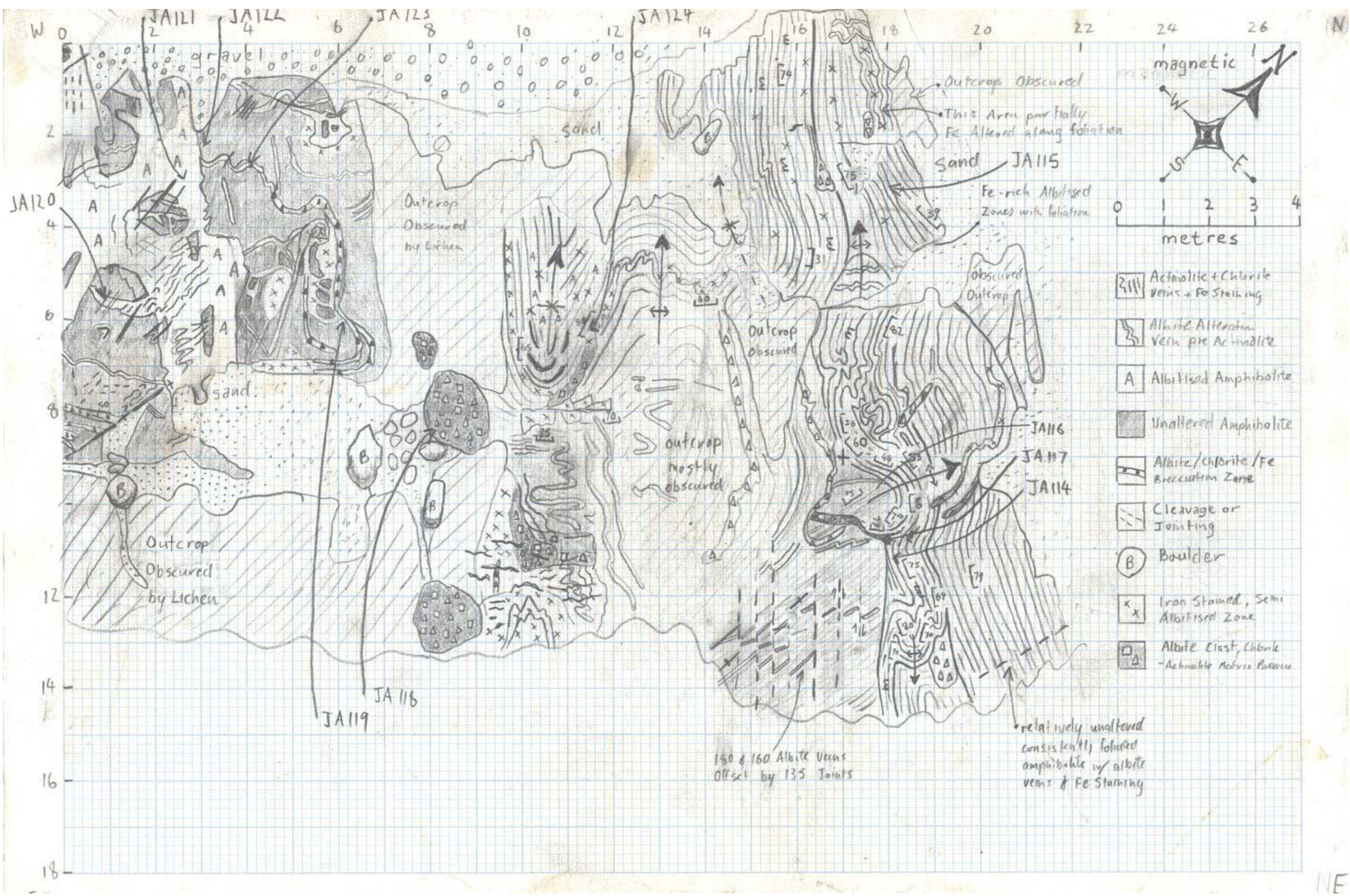


1:5,000 Geological Map of Fullarton Gorge - Map 2
Creek Junction
Creek
Planar Fabric in pegmatitic Rocks
Linear Fabric in Granitic Rock
Foliated Granite
no outcrop

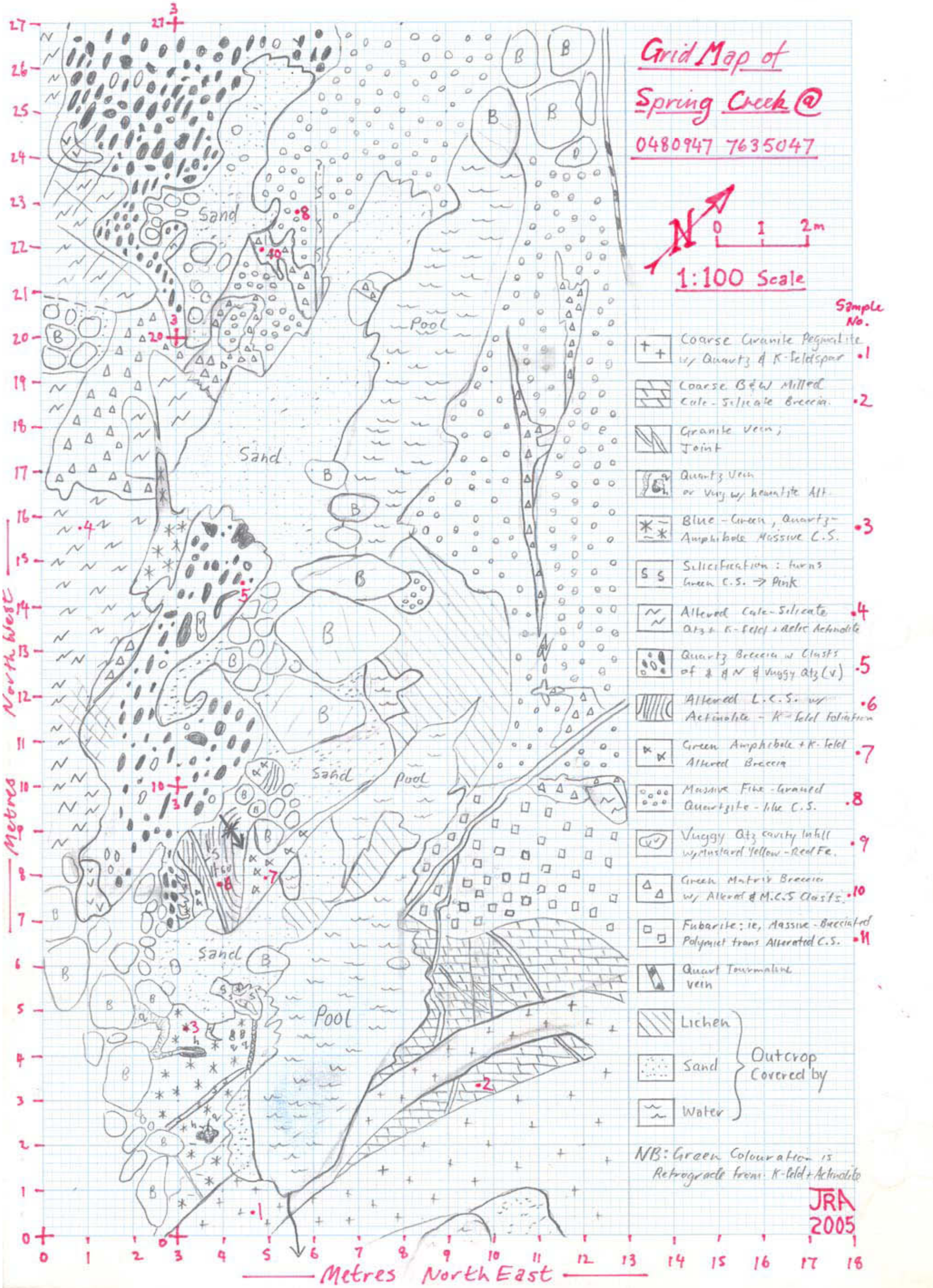
Appendices


Map of Fullerton Gorge Section
1:200 Scale
NE
SE
NW
SW
Gorge
Wall
Fullerton
River
Rock Pool
Laminated Calc-Silicate
Foliated Calc-Silicate pseudo mylonite
Qa
Gorge Wall
Foliated Amphibolite
Chlorite Clast Breccia
Chlorite Matrix Breccia
Dolerite Clast Breccia
Albite + Chloritised Zone
10m
0473096
7653404
0473052
7653413

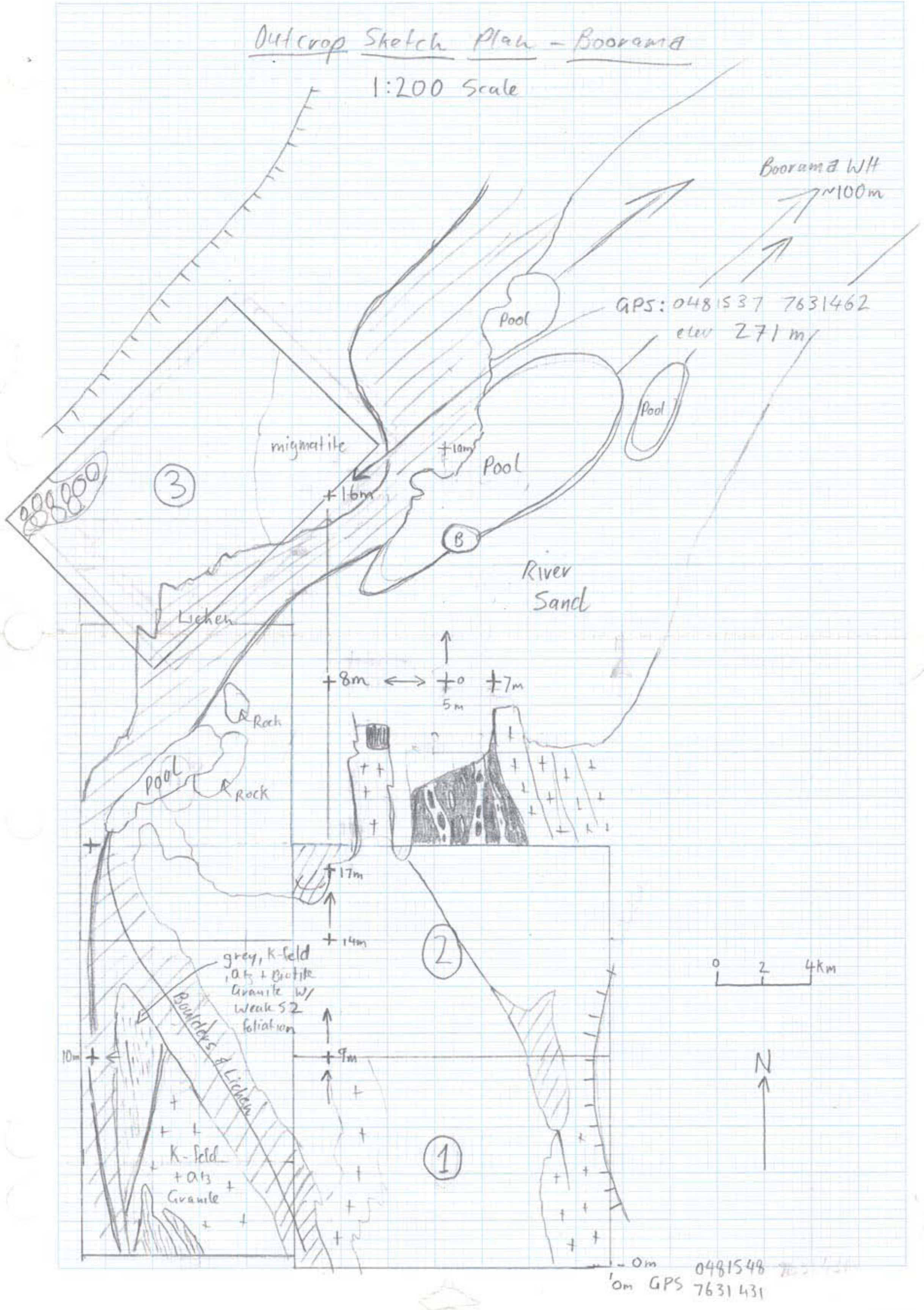
Appendices



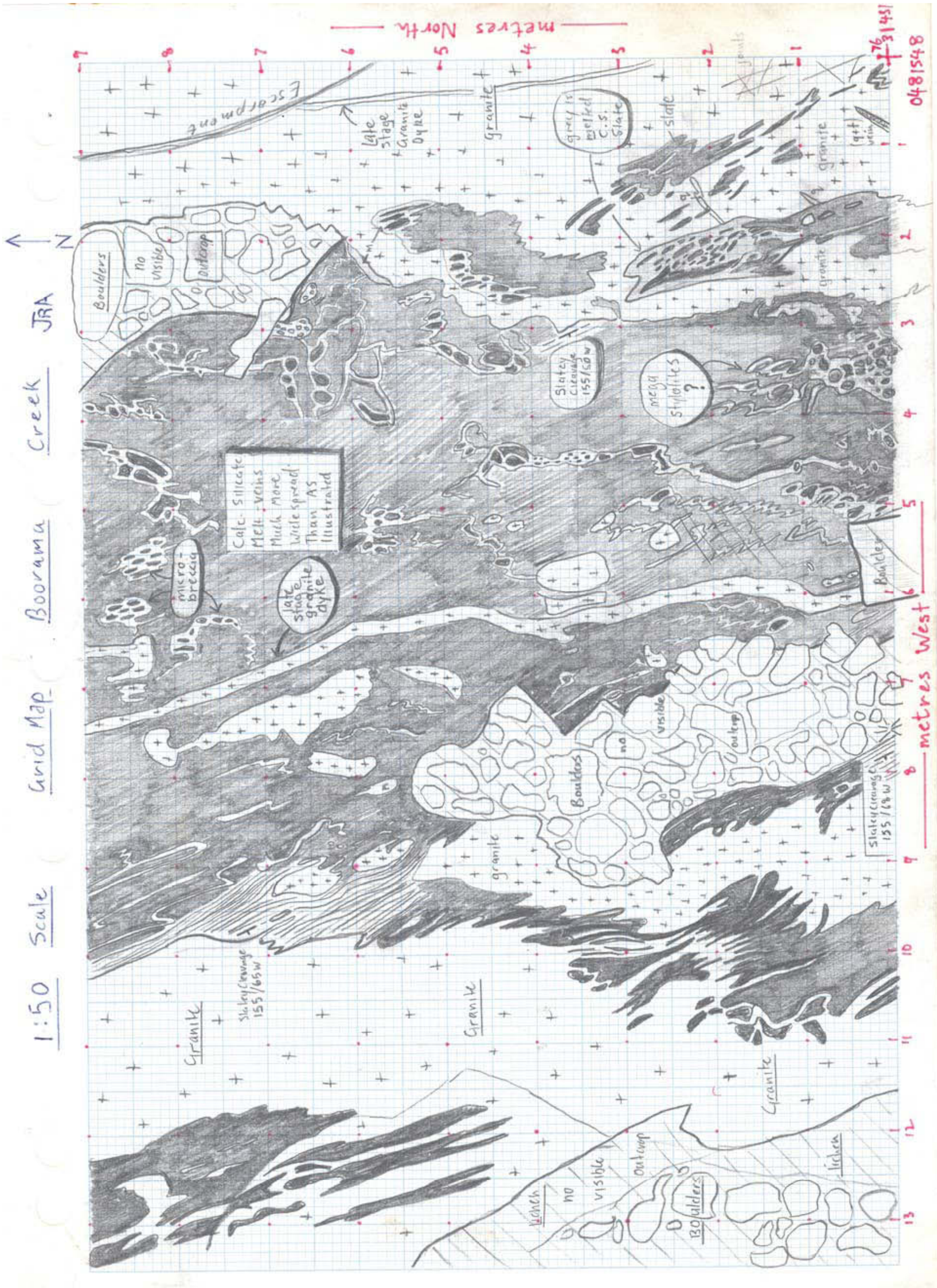
W
N
NE
magnetic
N
W
S
E
0 1 2 3 4
metres
Actinolite + Chlorite Veins + Fe Staining
Albite Alteration Vein pre Actinolite
A Albitised Amphibolite
Unaltered Amphibolite
Albite/chlorite/Fe Brecciation Zone
Cleavage or Jointing
B Boulder
Iron Stained, Semi Albitised Zone
Albite Clast, Chlorite -Actinolite Matrix Breccia
gravel
sand
Outcrop Obscured by Lichen
Outcrop Obscured
This Area partially Fe Altered along foliation
Fe-rich Albitised Zones with foliation
Obscured Outcrop
outcrop mostly obscured
relatively unaltered consistently foliated amphibolite w/ albite veins & Fe Staining
180 & 160 Albite Veins Offset by 135 Joints
JA111
JA122
JA123
JA124
JA120
JA115
JA116
JA117
JA114
JA118
JA119



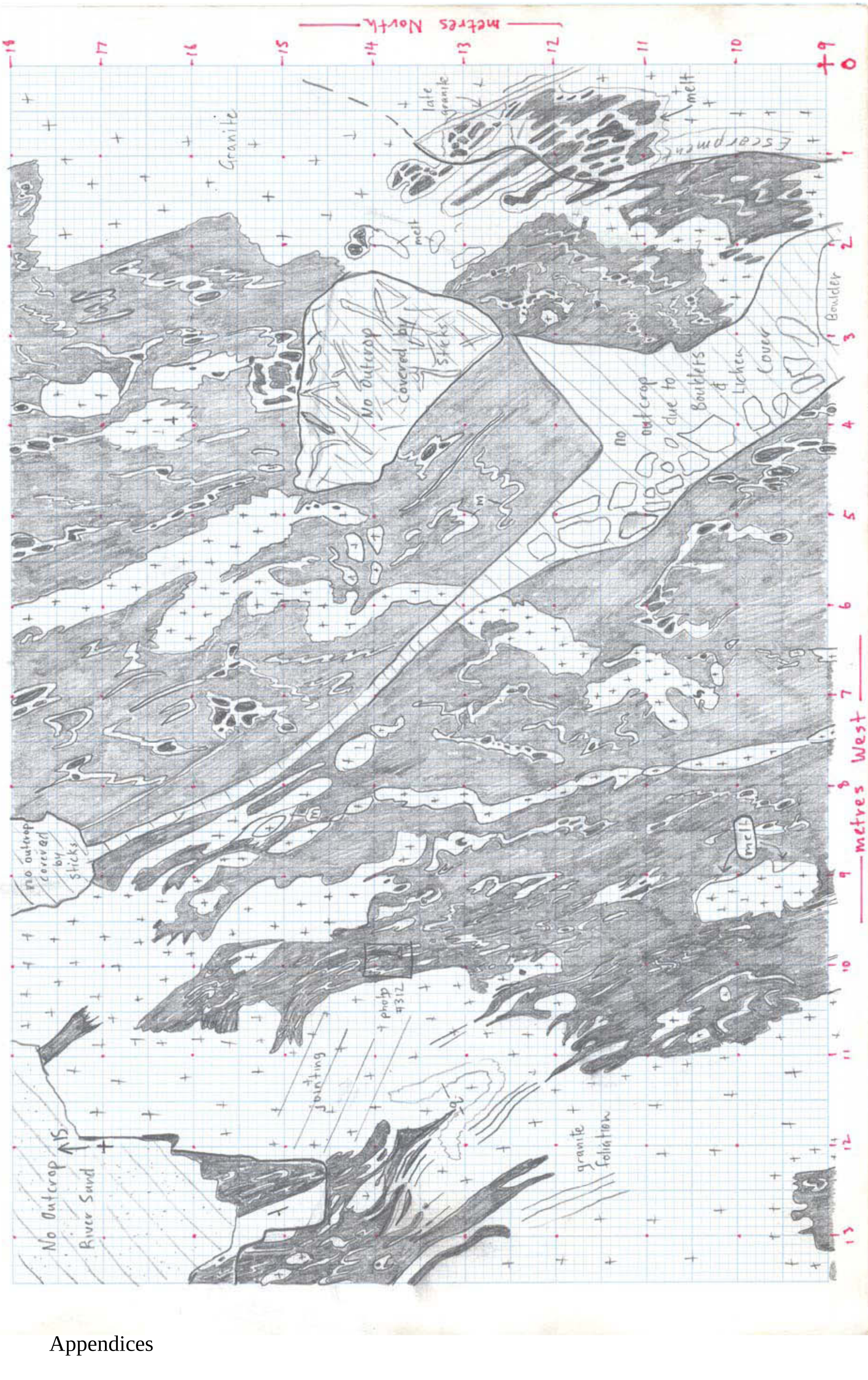
Grid Map of
Spring Creek @
0480947 7635047
N
0 1 2m
1:100 Scale
Sample No.
Coarse Granite Pegmatite w/ Quartz & K-feldspar •1
Coarse B&W Milled Calc-Silicate Breccia. •2
Granite Vein; Joint
Quartz Vein or Vug w/ hematite Alt.
Blue-Green, Quartz-Amphibole Massive C.S. •3
Silicification: turns Green C.S. → Pink
Altered Calc-Silicate Qtz + K-feld + Relic Actinolite •4
Quartz Breccia w Clasts of & & N & Vuggy Qtz (v) •5
Altered L.C.S. w/ Actinolite - K-feld Foliation •6
Green Amphibole + K-feld Altered Breccia •7
Massive Fine-Grained Quartzite-like C.S. •8
Vuggy Qtz cavity Infill w/ Mustard Yellow - Red Fe. •9
Green Matrix Breccia w/ Altered & M.C.S Clasts. •10
Fubarite: ie, Massive-Brecciated Polymict trans Alterated C.S. •11
Quart Tourmaline vein
Lichen
Sand
Water
Outcrop Covered by
NB: Green Colouration is Retrograde from K-feld + Actinolite
JRA 2005
Sand
Pool
B
Metres North West
Metres North East
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0


Outcrop Sketch Plan - Boorama
1:200 Scale
Boorama WH
~100m
GPS: 048537 7631462
elev 271 m
Pool
Pool
Pool
migmatite
3
+10m
+16m
B
River
Sand
Lichen
+8m
+0
5m
+7m
Rock
Pool
Rock
+17m
+14m
2
grey, K-feld
, Qtz + Biotite
Granite w/
weak S2
foliation
Boulders & Lichen
0 2 4km
10m
+9m
N
K-feld
+ Qtz
Granite
1
0m
0481548
0m GPS 7631431

Appendices



1:50 Scale Grid Map Boorama Creek JRA
N
metres North
metres West
Escarpment
late stage Granite Dyke
grey is melted C.S. Slate
slate
granite
Slatey Cleavage 155/60W
mega stylolites ?
Calc-Silicate Melt-Veins Much More Wide spread Than AS Illustrated
micro-breccia
late stage granite dyke
Boulders no visible outcrop
Slatey Cleavage 155/65W
Granite
lichen
0481548
7631451


metres North
metres West
Granite
late granite
melt
Escarpment
Boulder
No outcrop covered by sticks
no outcrop due to Boulders & Lichen Cover
no outcrop covered by sticks
photo #312
jointing
granite foliation
No Outcrop River Sand
15


Grid Map of Boorama #3
metres North West
metres South West
strongly foliated migmatite
Actinolite core in Granite Vein
locally & weakly foliated migmatite
migmatized granite - amphibolite
gradation from granite into migmatite
#310
Sand
jointing
no outcrop - Lichen

Appendices

Appendix 5c: PIMA data

Output from ‘the spectral geologist’ software

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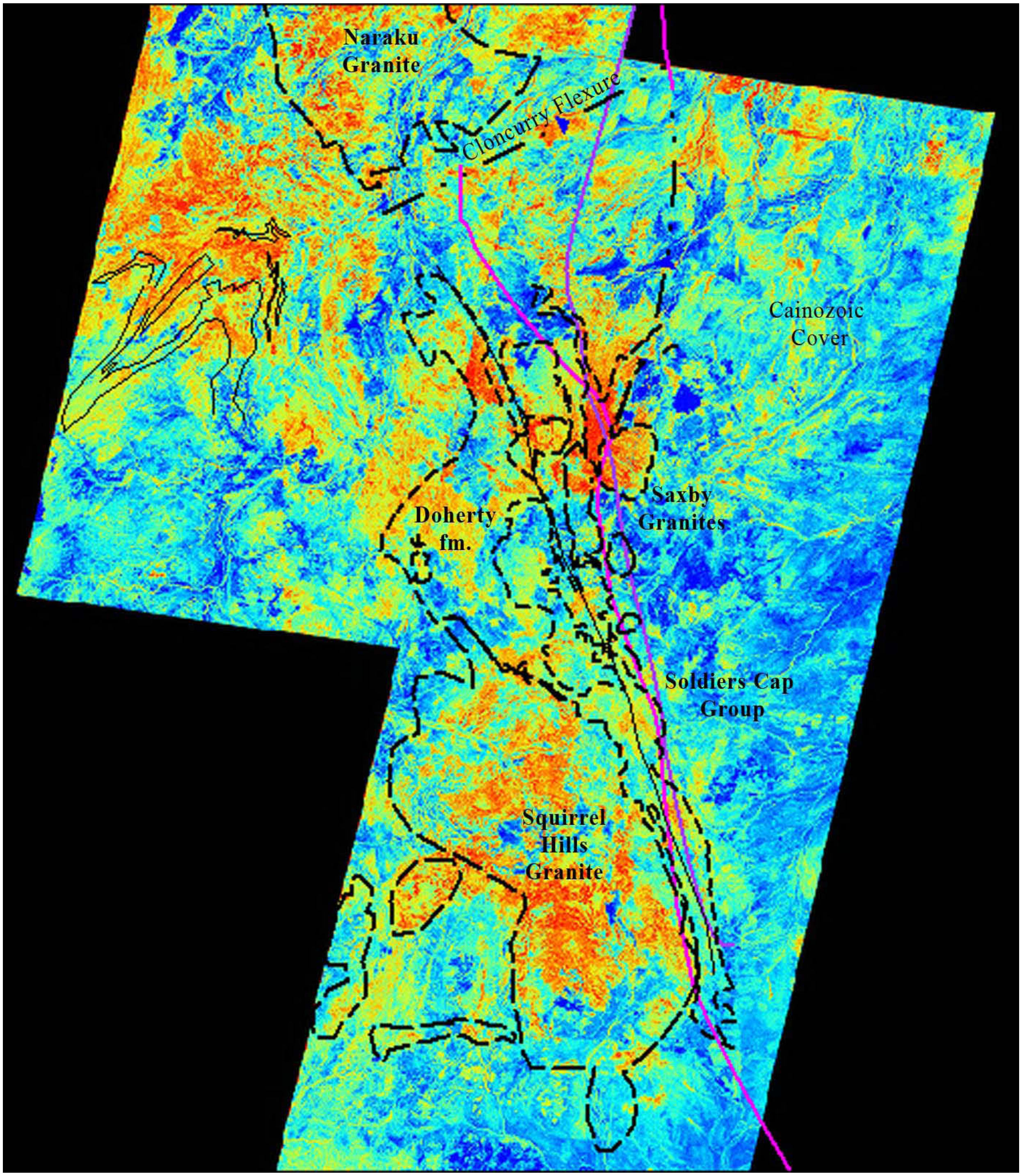
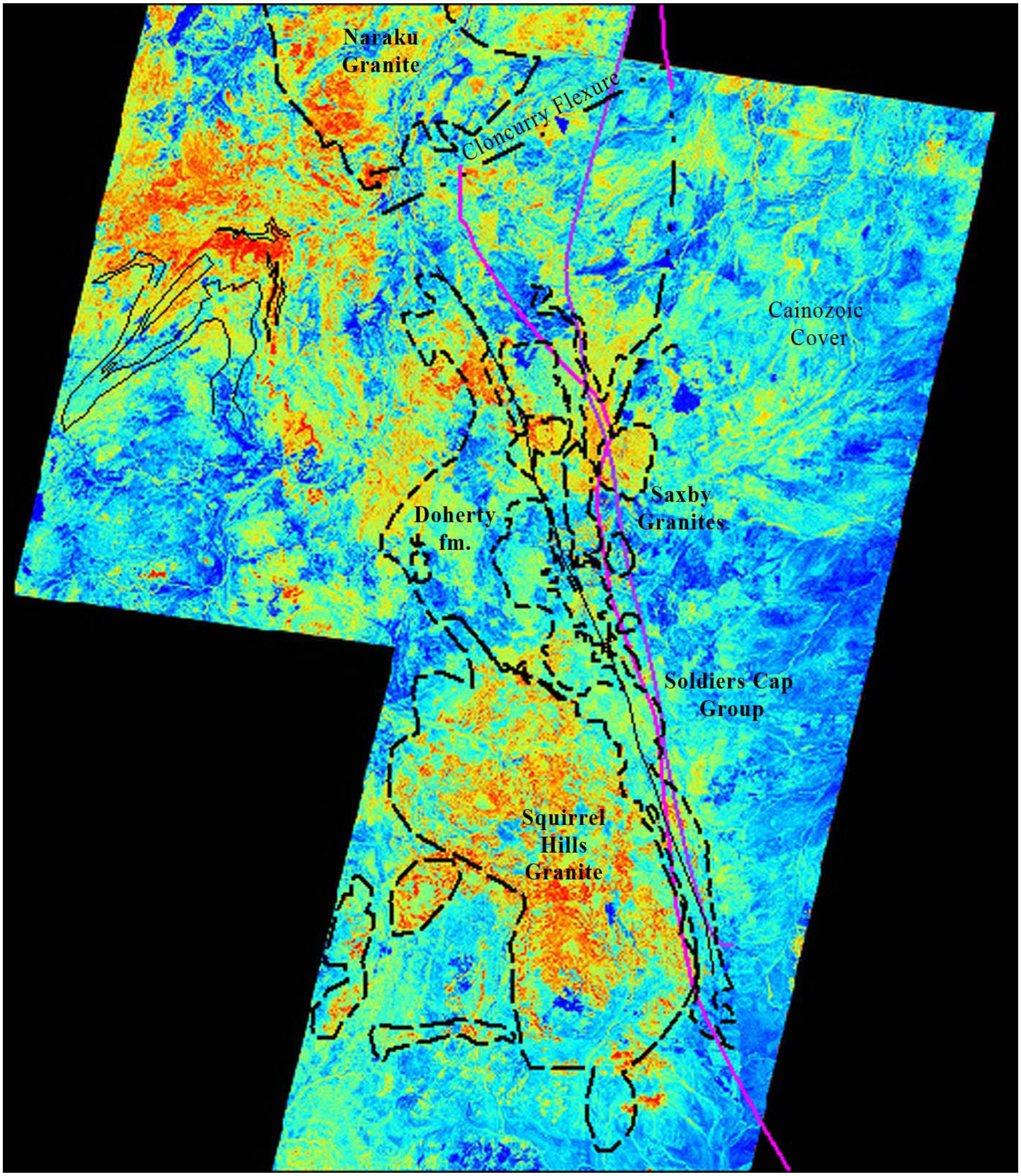
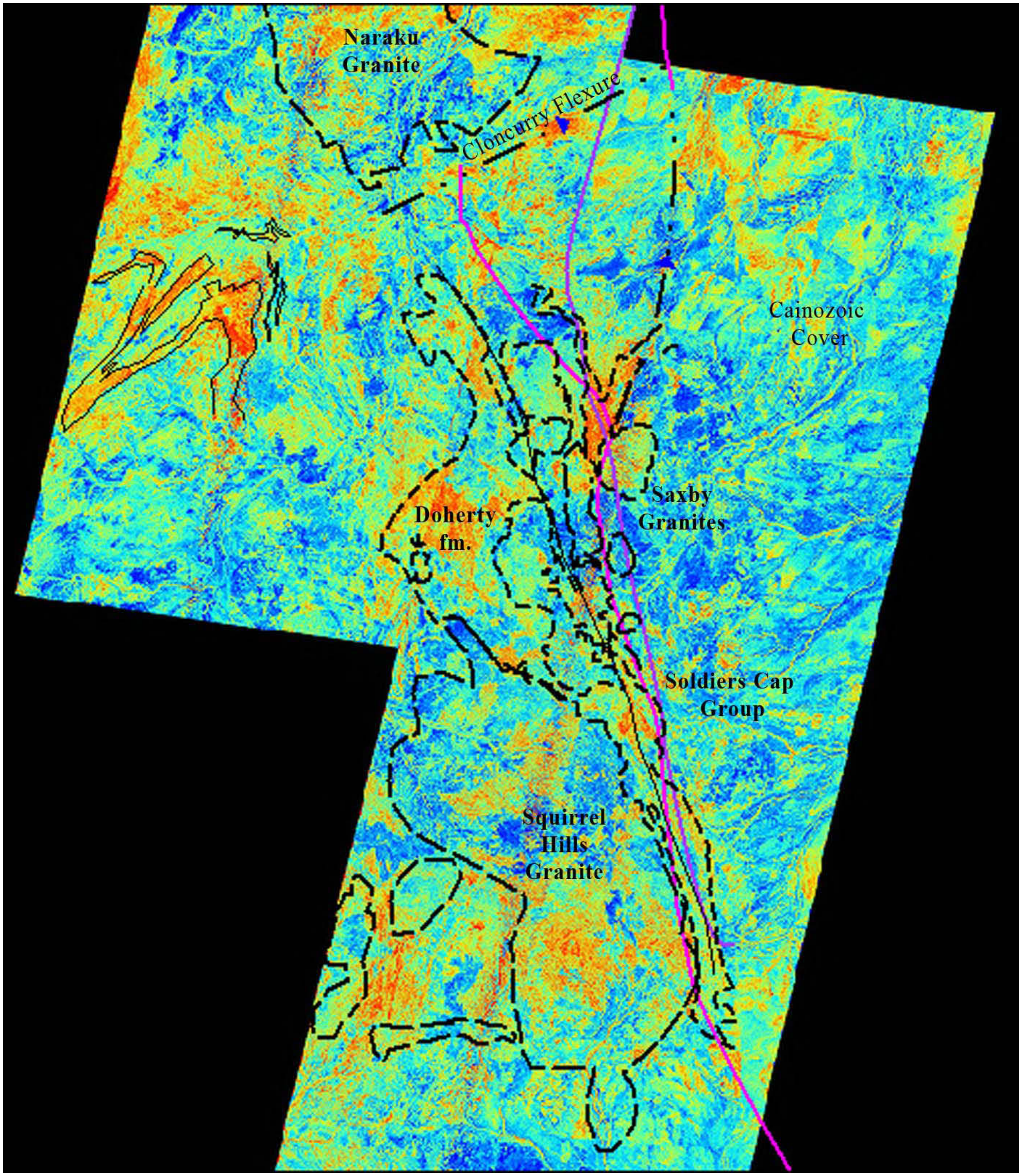
Appendix 5d: ASTER Mineral Index Maps



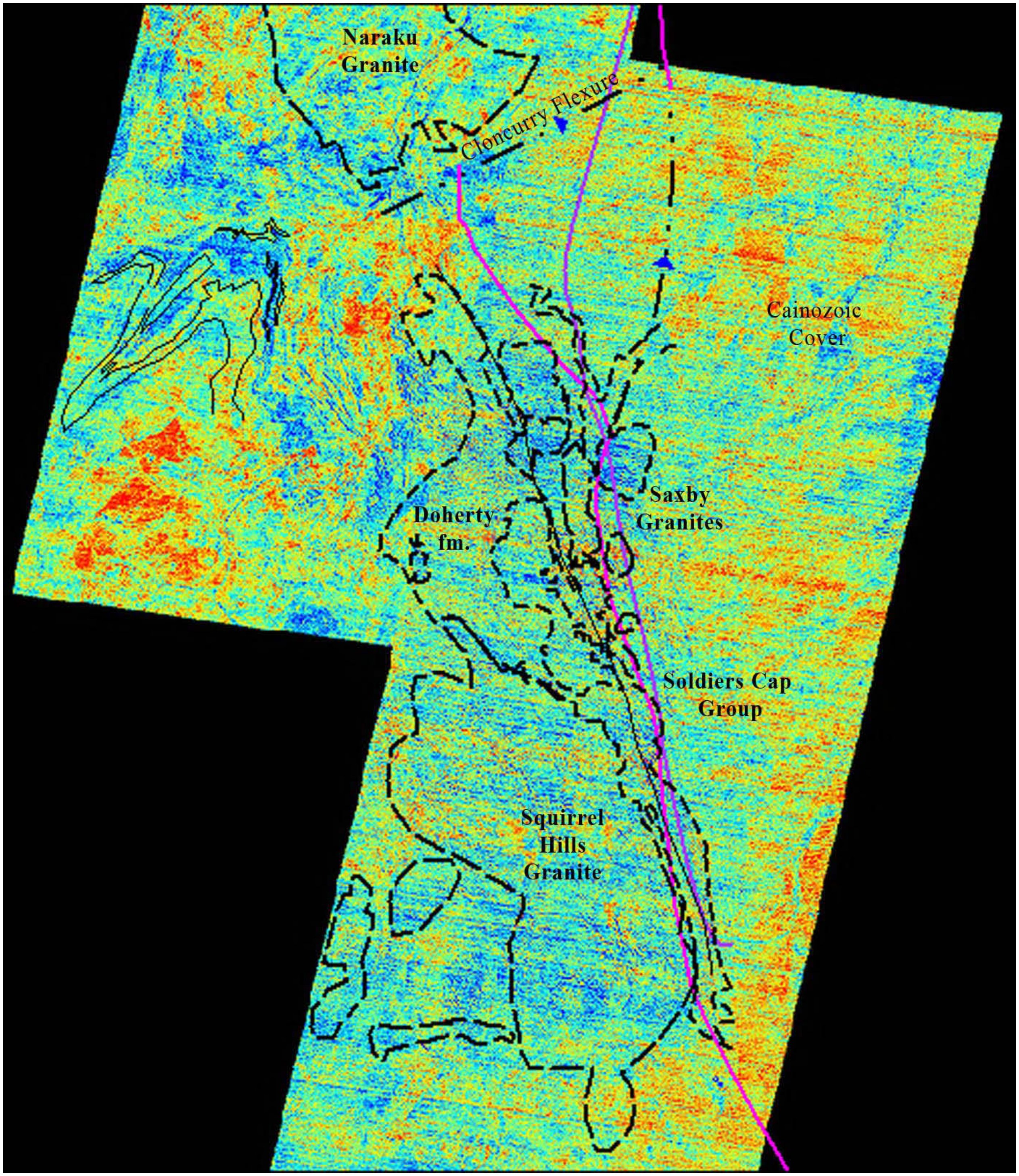
Alteration Index – Volesky, 2003



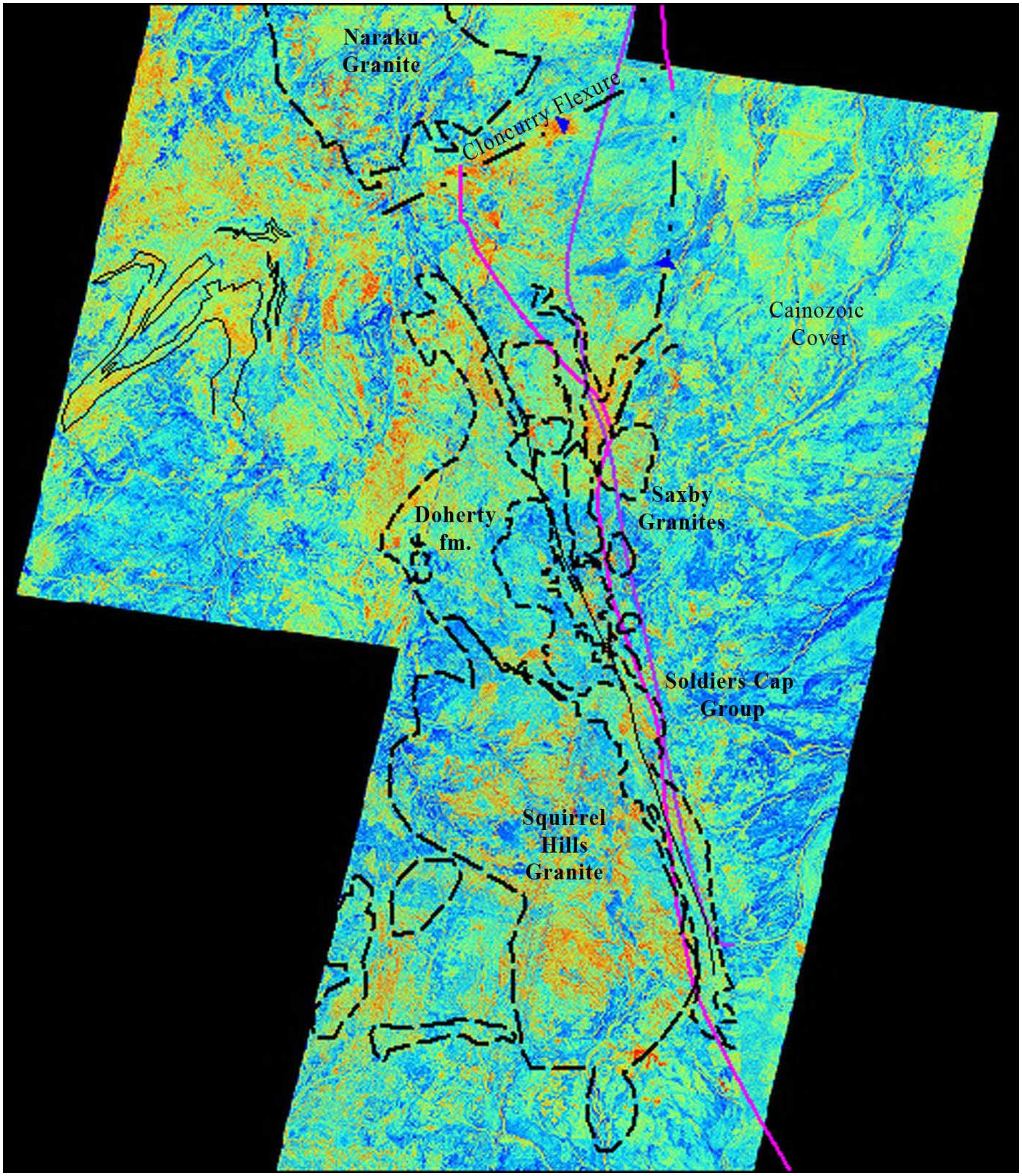
Amphibole Mineral Index – Bierwirth, 2002



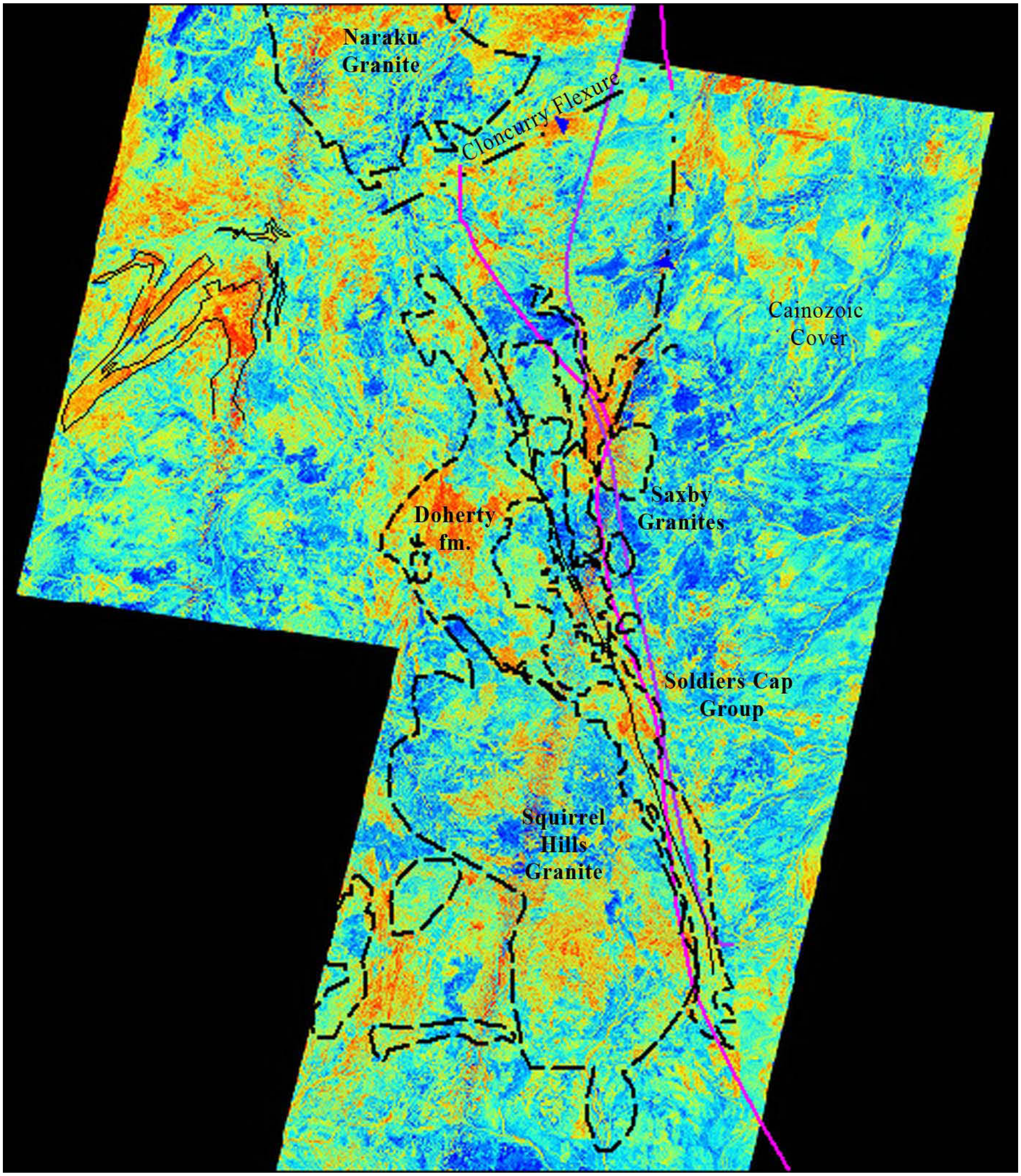
Amphibole-MgOH Mineral Index – Hewson et al., 2005



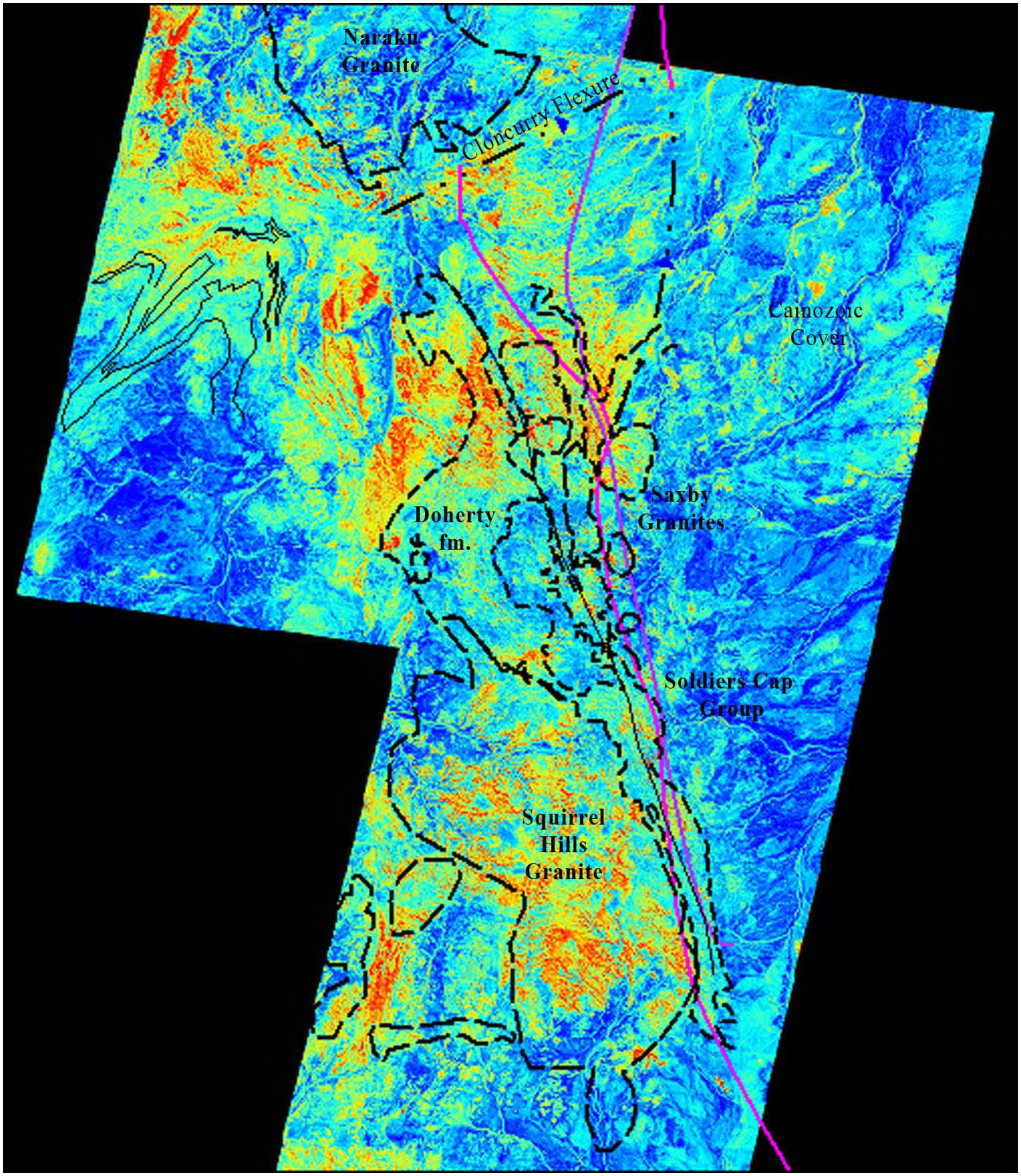
Carbonate Mineral Index - Ninomiya and Fu, 2002



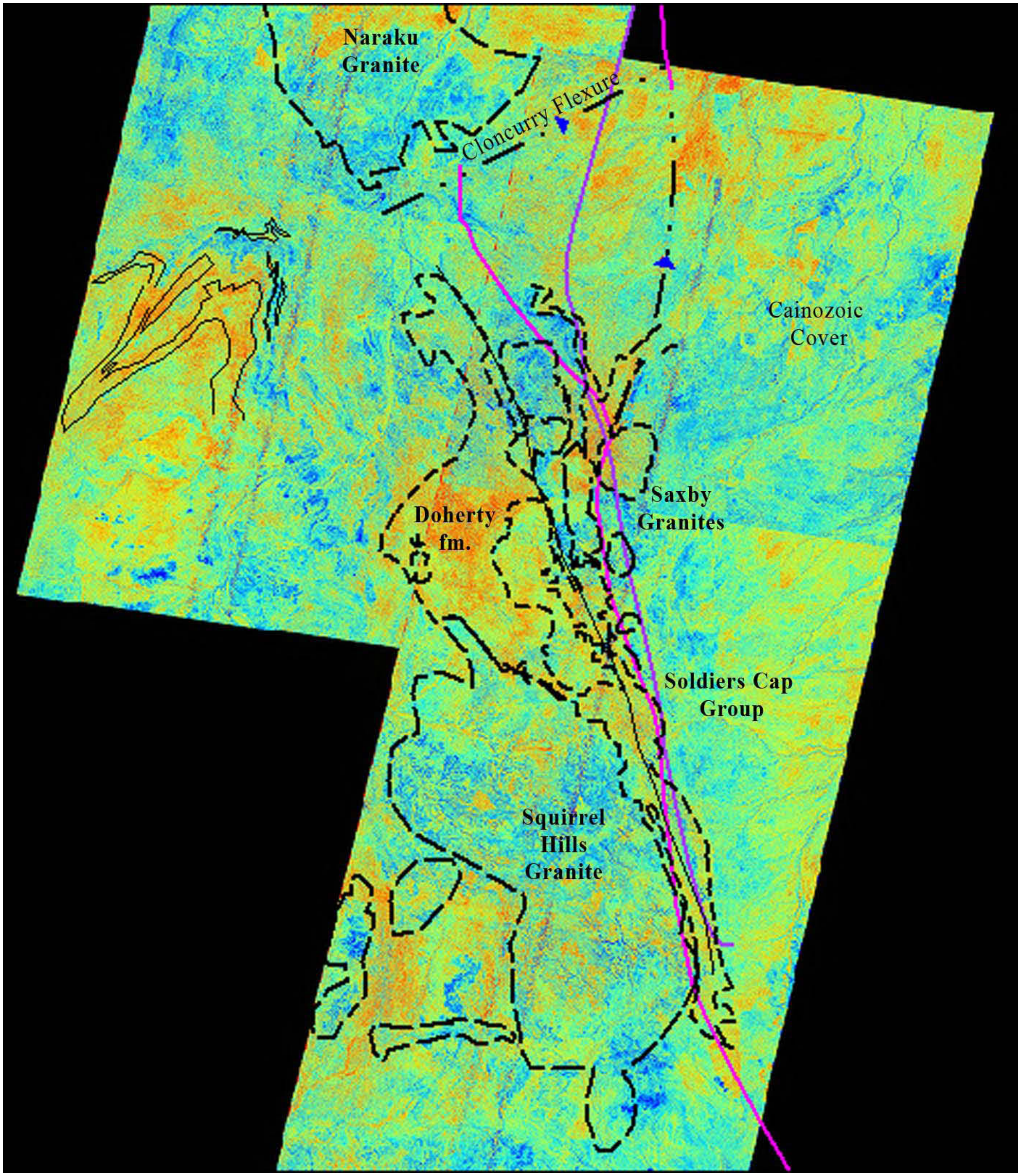
Calcite-Carbonate-Chlorite-Epidote Mineral Index – Rowan et al., 2003



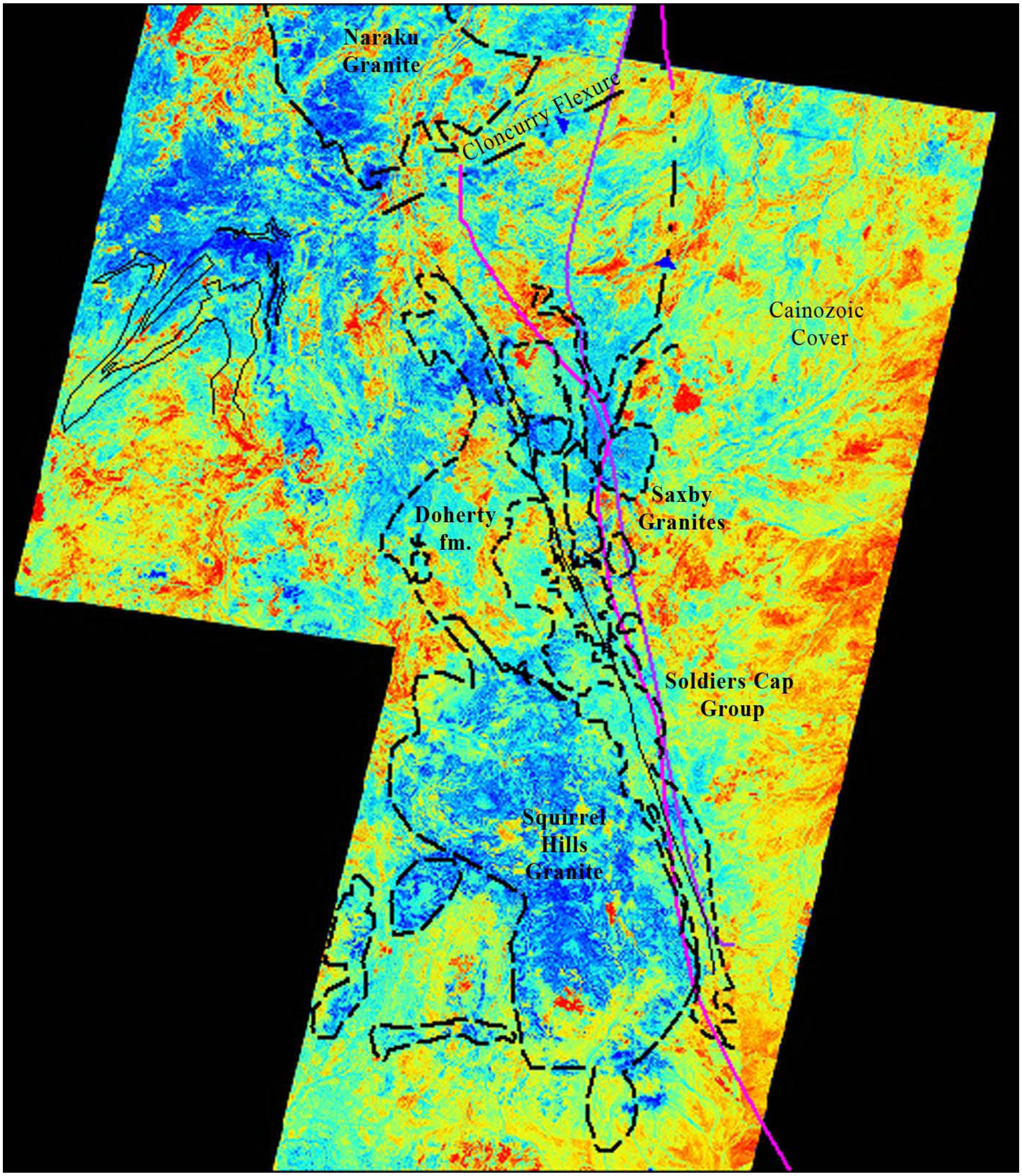
Clay Mineral Index – Bierwirth, 2002



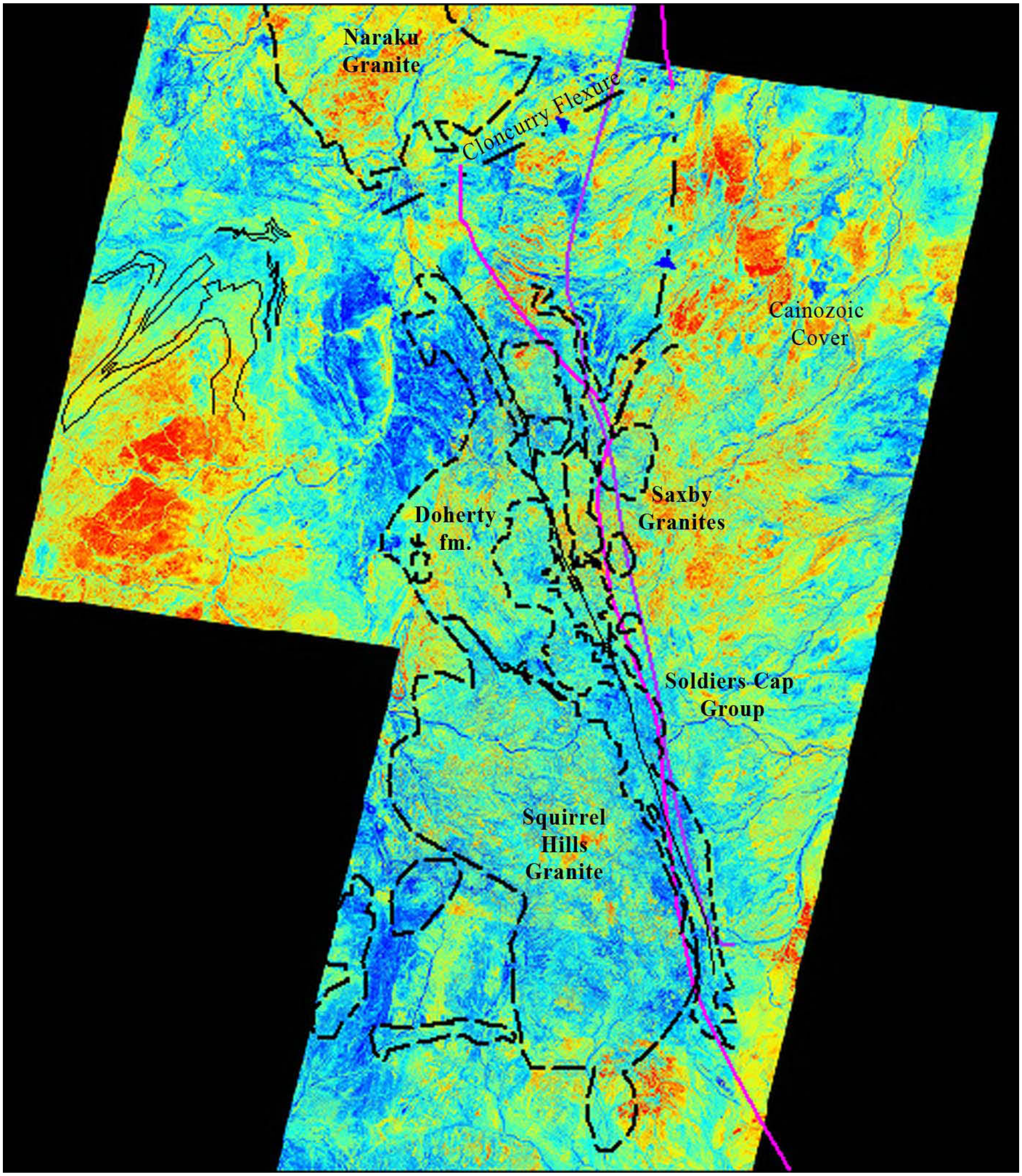
Dolomite Mineral Index – Rowan et al., 2003



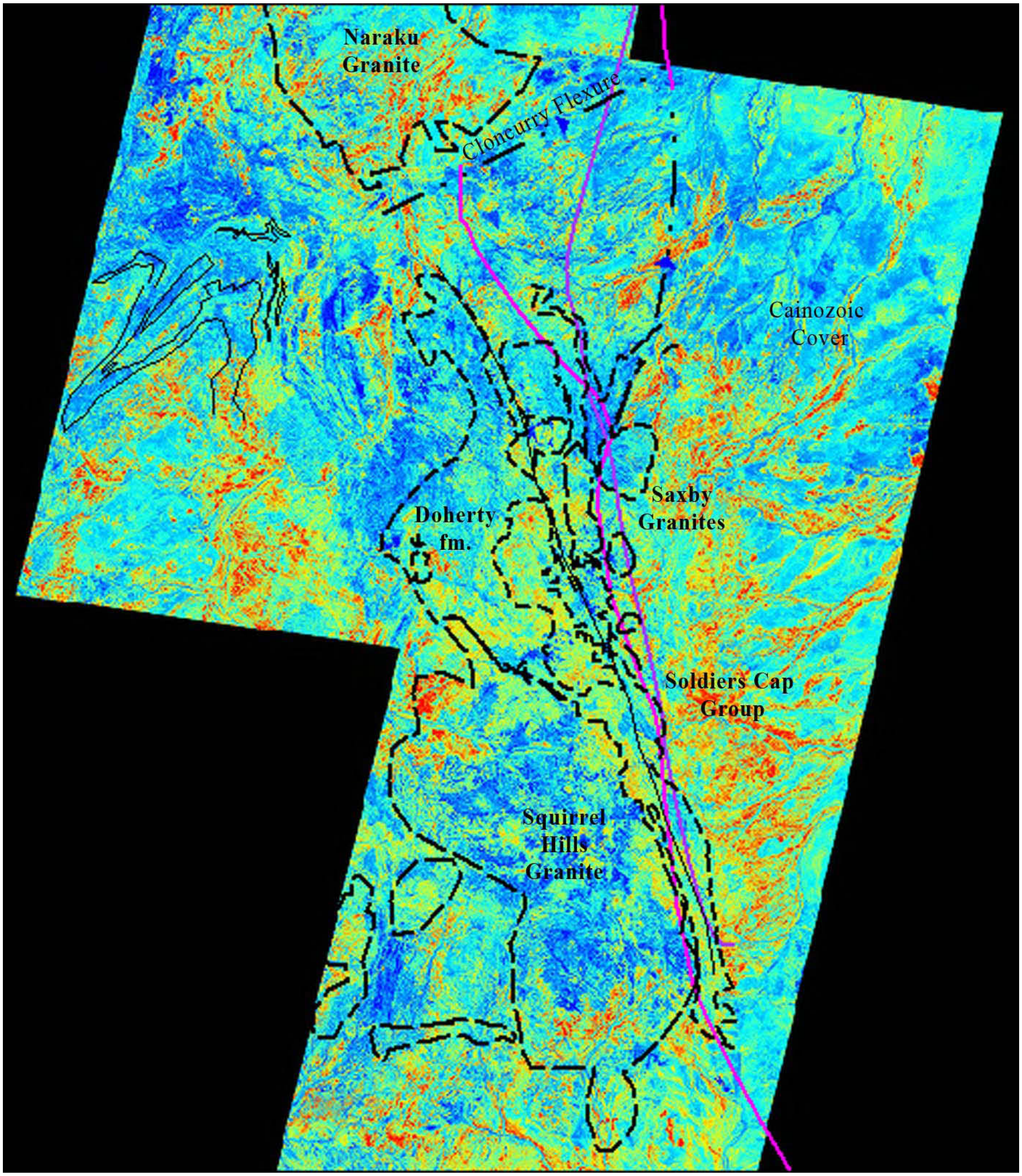
Epidote-Chlorite-Amphibole Mineral Index – Kalinowski and Oliver, 2004



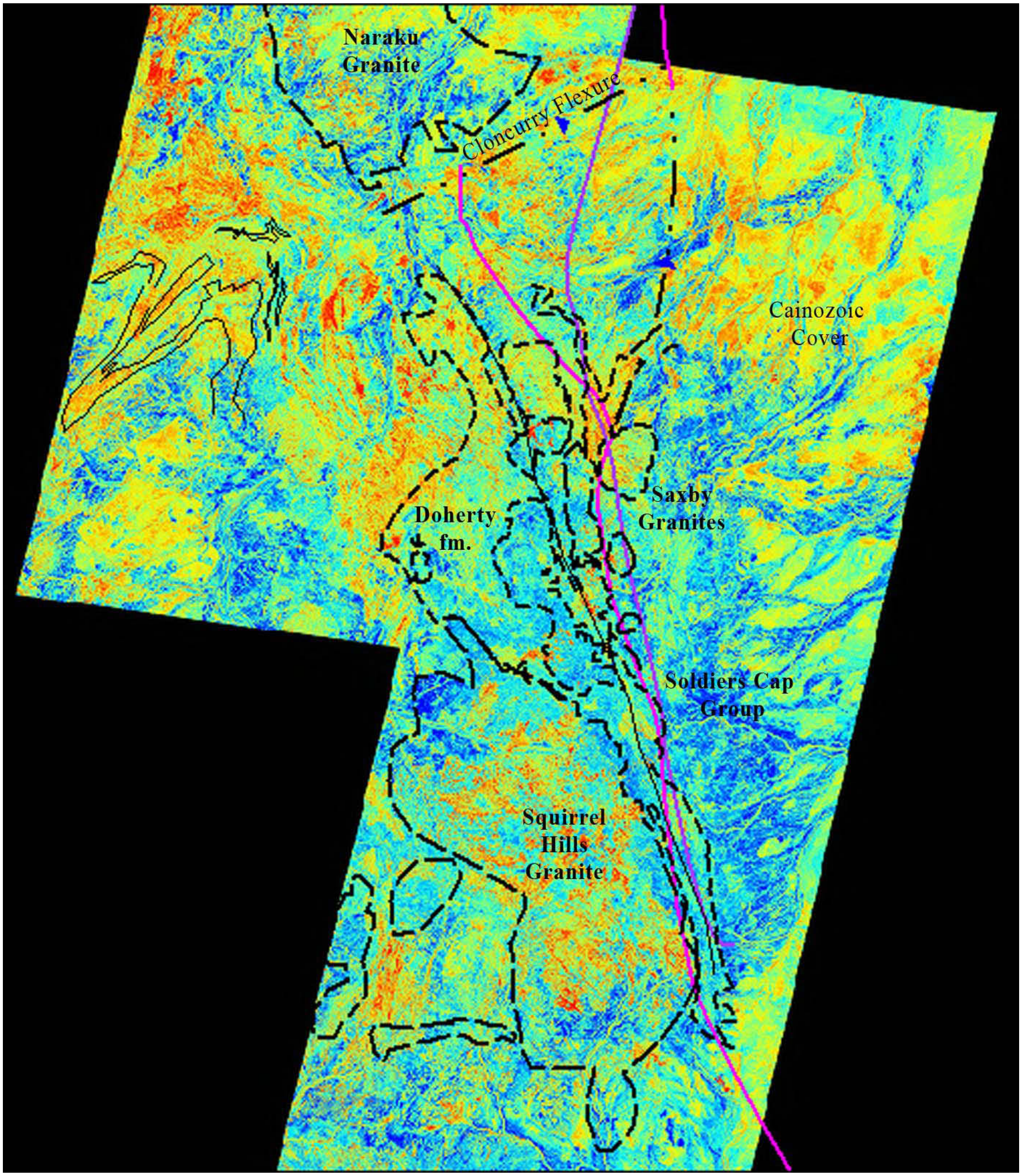
Ferric Oxides Mineral Index – Kalinowski and Oliver, 2004



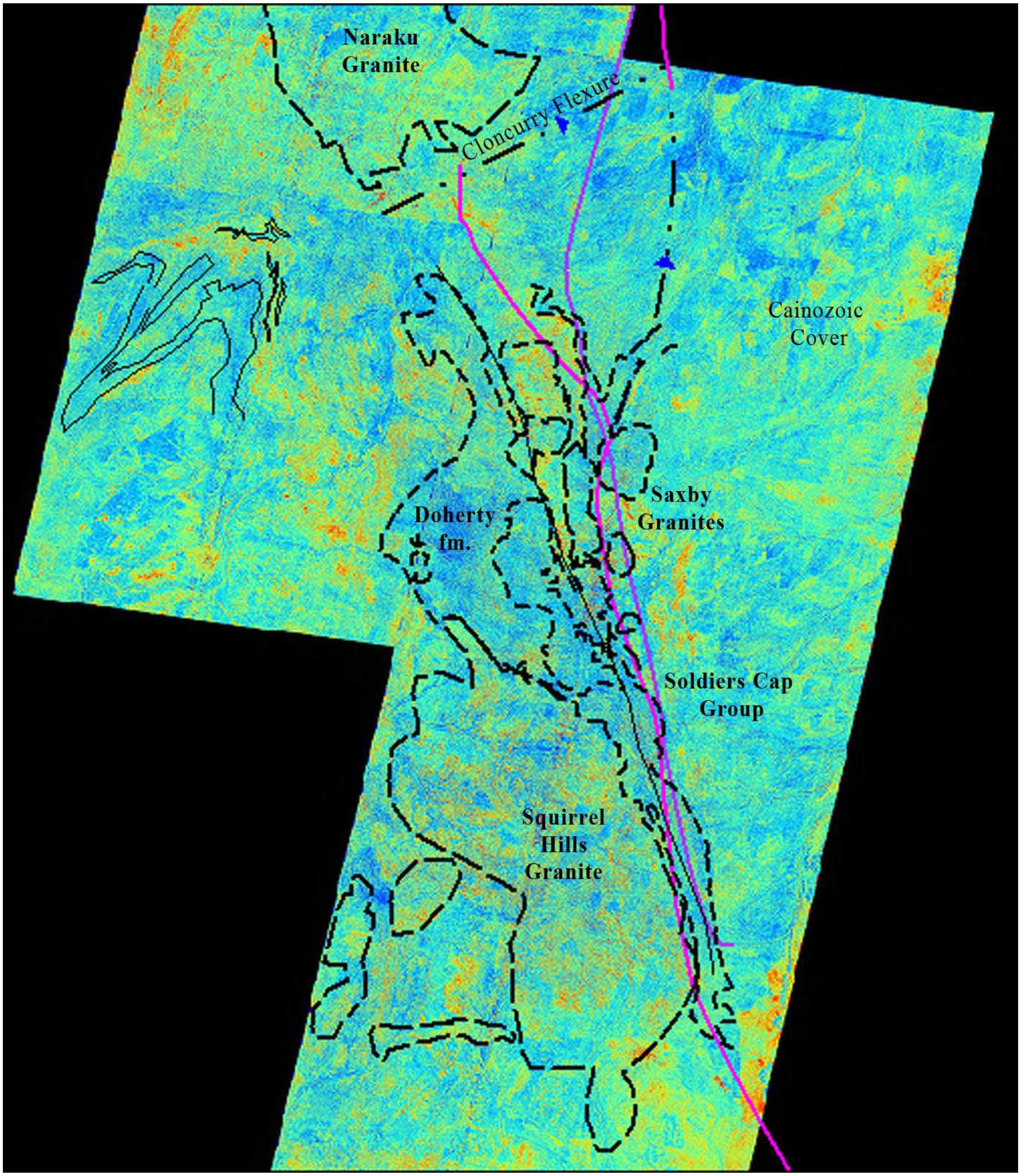
Ferric Iron Mineral Index – Rowan et al., 2004



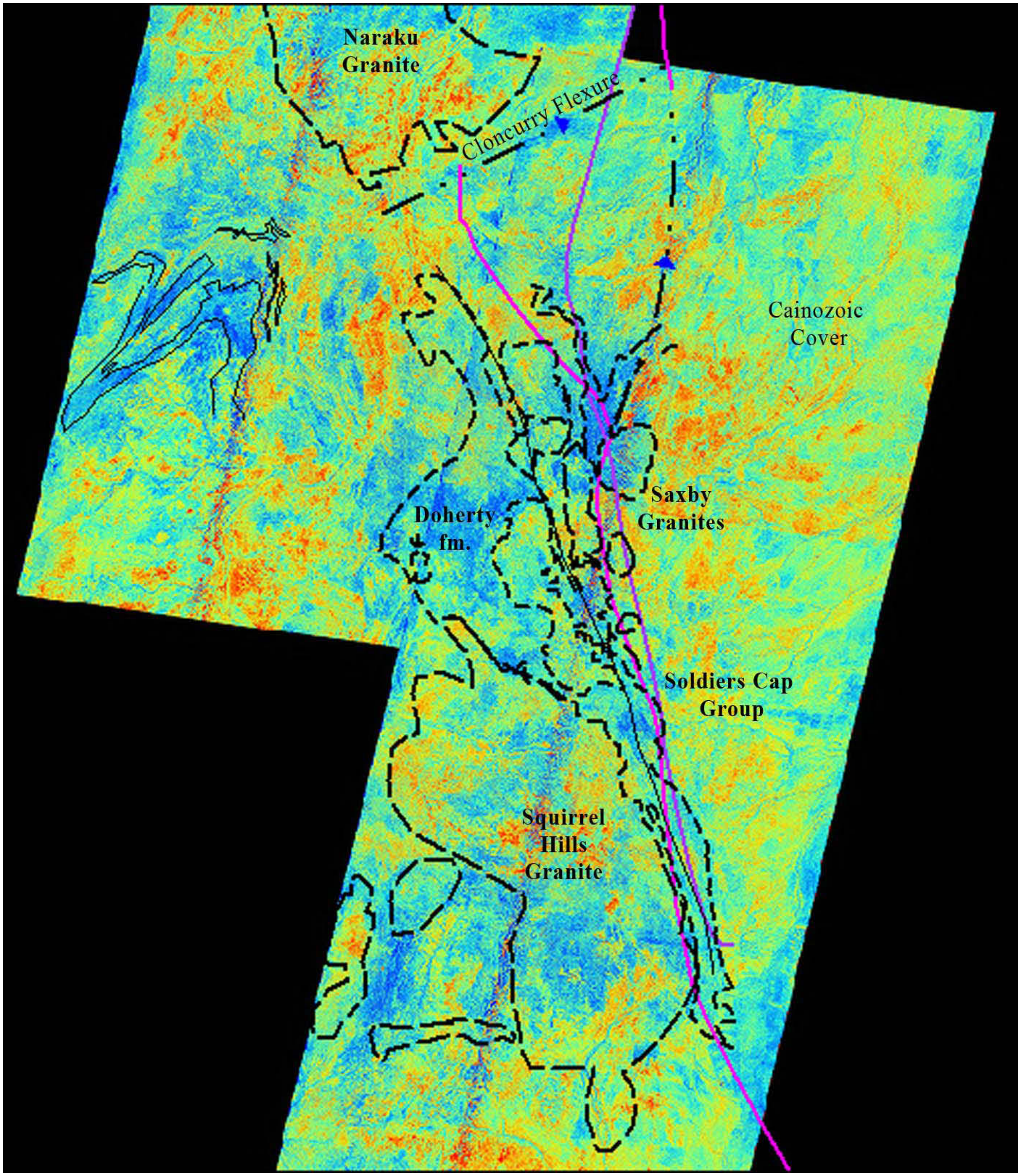
Ferrous Iron Mineral Index – Rowan et al., 2003



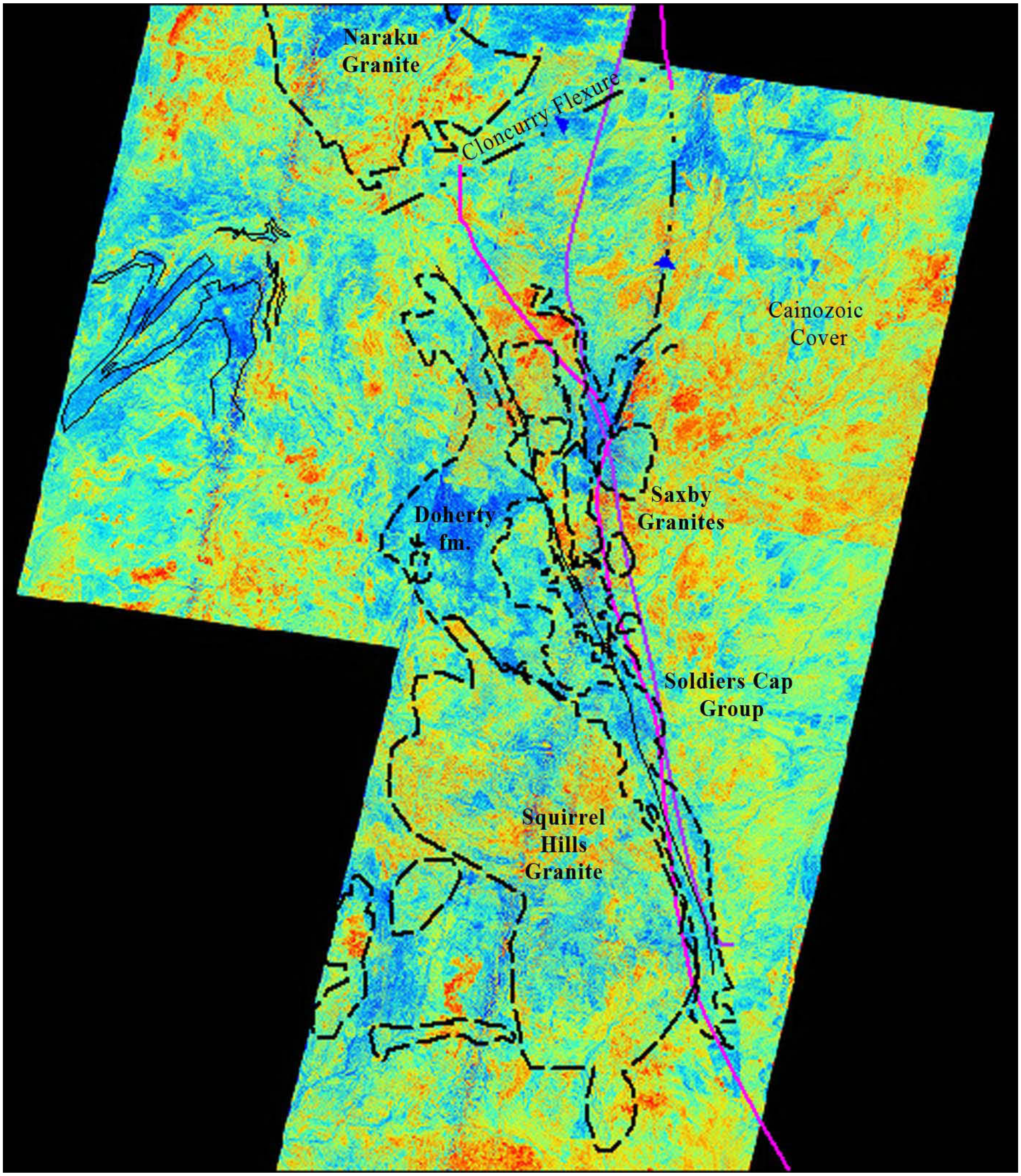
Ferrous Silicates Mineral Index – Kalinowski and Oliver, 2004



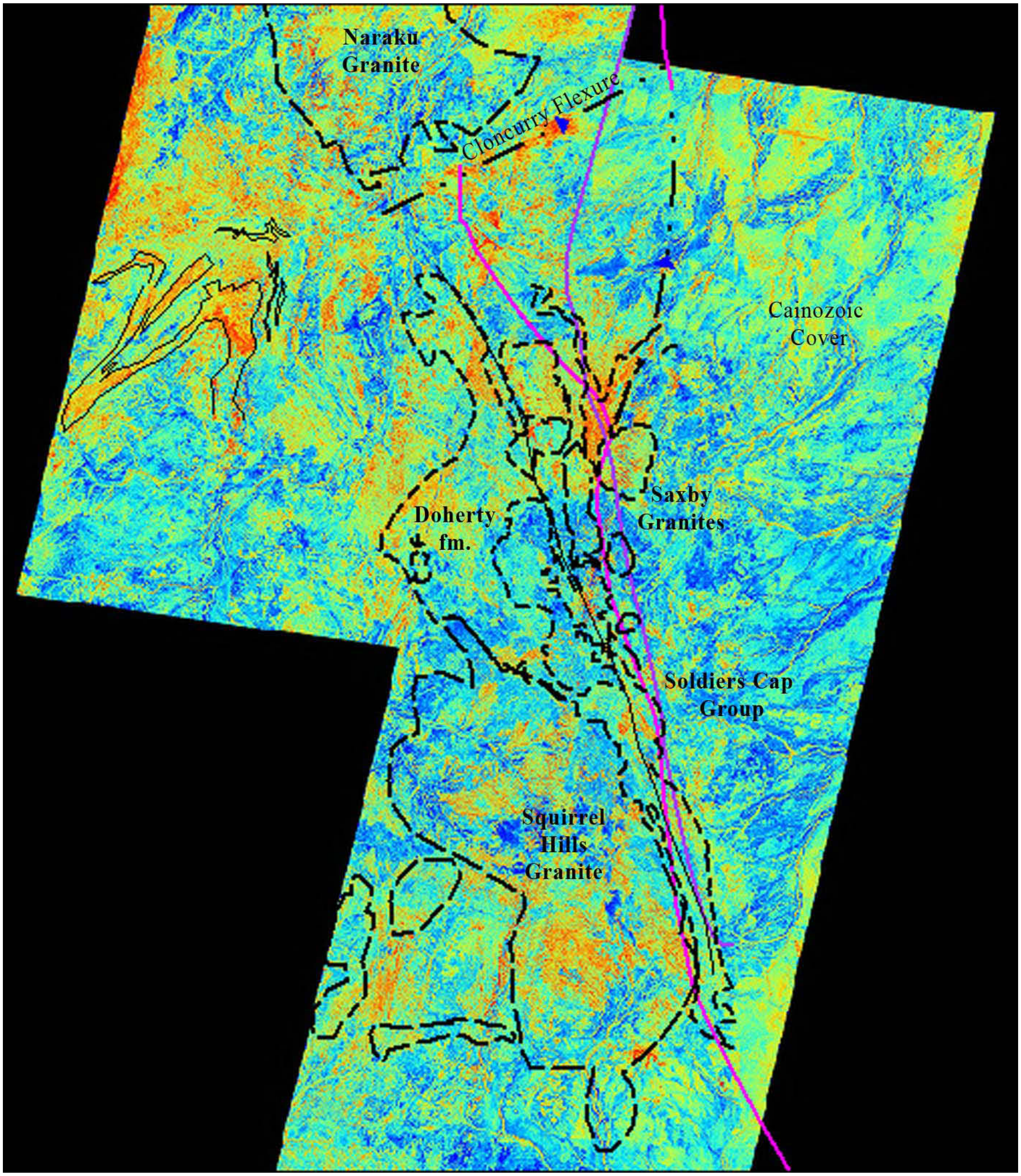
Kaolinite Mineral Index – Hewson et al., 2005



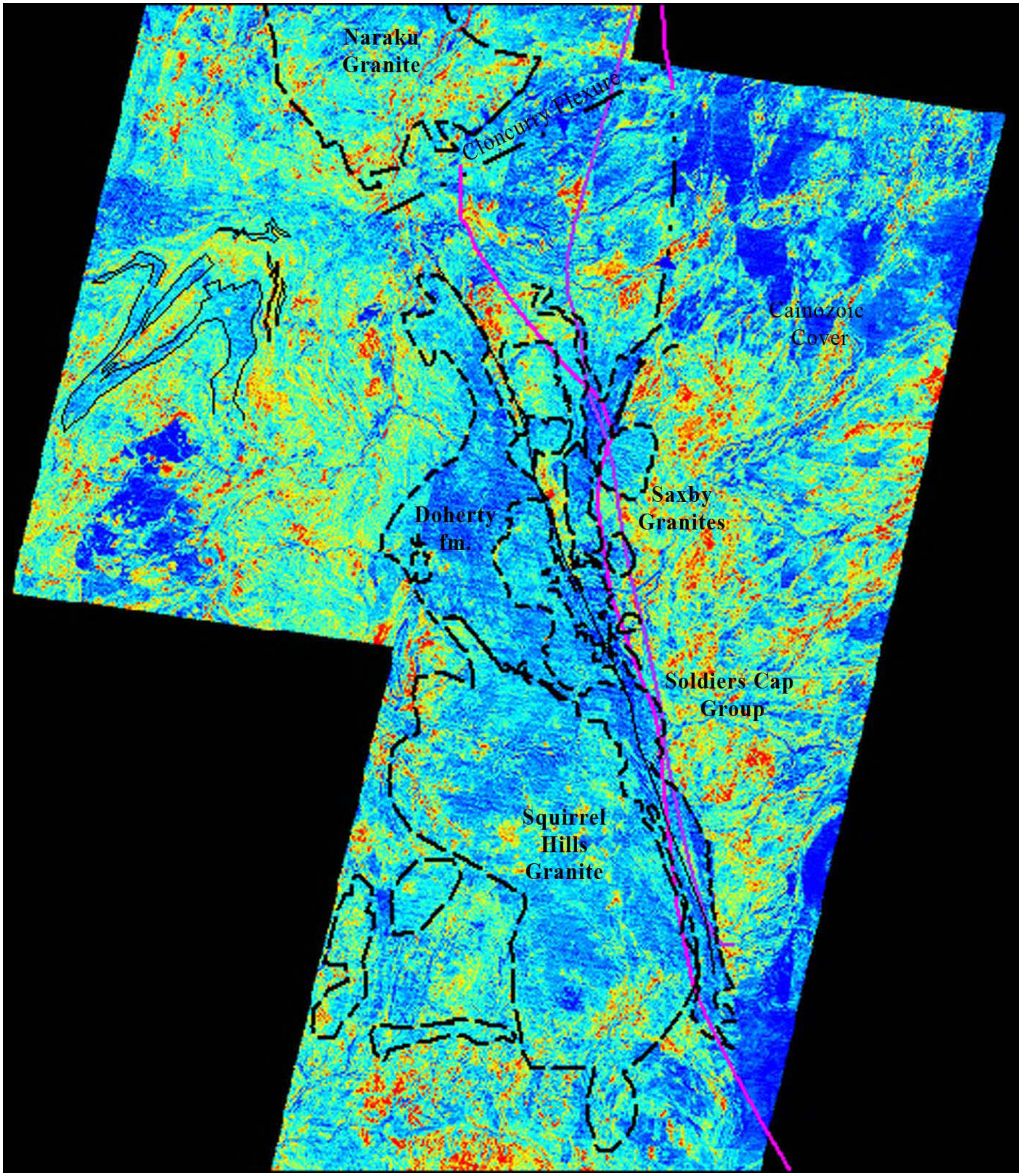
Muscovite Mineral Index – Hewson et al., 2005



Phengitic Mineral Index – Hewson et al., 2005



Quartz Mineral Index – Ninomiya and Fu, 2002



Sericite-Muscovite-Illite-Smectite Mineral Index – Rowan and Mars, 2003

Appendix 5e: Magnetic Susceptibility Data

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Appendix 5f

Granitoid Geochemistry Data

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Appendix 6: Publications, Presentations, Courses and Workshops

Publications

J.R. Austin, Digging deeper with worms: Finding Structure in Geophysics, Mount Isa Eastern Succession. In A.C. Barnicoat and R.J. Korsch (Eds), 2004 Abstract, published in the Predictive Mineral Discovery Cooperative Research Centre, Extended Abstracts from the June 2004 Conference.

J.R. Austin, Digging deeper with worms***:*** EGRU Newsletter, December 2004

Damien Foster**, James Austin**, Revised chronostratigraphy for the Mount Isa Inlier with emphasis on the Eastern Succession. In I2+3 - Total systems analysis of the Mt Isa Eastern Sucession, pmd*CRC, 2005.

Tom Blenkinsop, Cameron Huddlestone-Holmes, Damien Foster, Geordie Mark, **Jim Austin**, Mark Edmiston, Piter Lepong, Arianne Ford, Barry Murphy, Michelle Stark, 3D Model and Crustal Architecture of the Mt Isa Eastern Succession. In I2+3 - Total systems analysis of the Mt Isa Eastern Sucession, pmd*CRC, 2005.

J.R. Austin 2005**,** The Cloncurry Lineament: Interpretation of a major crustal worm. In I2+3 - Total systems analysis of the Mt Isa Eastern Sucession, pmd*CRC, 2005.

J.R. Austin, 2005 (abstract). The Cloncurry Lineament: Interpretation of a major crustal worm. In: Structure, tectonics and ore mineralisation processes, Conference Volume, EGRU contribution 64

M. J. Rubenach, T. G. Blenkinsop, and **J.R. Austin**. 2005. Structural and Metasomatic Evolution of the Mt Isa Block; Pre-Conference Field Trip, STOMP 2005.

Austin, J and Blenkinsop, T.G. 2006. Identifying mineralization patterns using auto-correlation: Mount Isa Eastern Succession, NW Queensland, Australia. In SEG 2006: Wealth Creation in the Minerals Industry; Conference Abstracts.

J.R. Austin, Defining mineralization patterns: Cloncurry, Qld: EGRU Newsletter, August 2006.

Austin, J and Blenkinsop, T.G. 2006. Identifying mineralization patterns using auto-correlation: Mount Isa Eastern Succession, NW Queensland, Australia; conference volume of the Australian Earth Science Convention, Melbourne 2006.

Tom Blenkinsop, Nick Oliver, **James Austin**, Mustafa Cihan, James Cleverly, Janine Josey (2007). Breccias and Fluids in the Eastern Fold Belt, Mount Isa Inlier. Breccia Symposium – *Economic Geology Research Unit*, *James Cook University* - June 2007

Austin, J. R. and Blenkinsop, T.G. 2007. The Cloncurry Lineament: Geophysical and geological evidence for a deep crustal structure in the Eastern Succession of the Mount Isa Inlier. Precambrian Research (in press).

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Damien R.W. Foster, **James R. Austin** (2007).The 1800 to 1610 Ma stratigraphic and magmatic history of the Eastern Succession, Mount Isa Inlier, and correlations with adjacent Paleoproterozoic terranes (in press).

Tom Blenkinsop, Nick Oliver, **James Austin**, Mustafa Cihan, James Cleverly, Janine Josey (2007). Breccias and Fluids in the Eastern Fold Belt, Mount Isa Inlier. Breccia Symposium – *Economic Geology Research Unit*, *James Cook University* - June 2007

Austin, J. R. and Blenkinsop, T.G. (XXXX). The Cloncurry Fault Zone: strain partitioning vs. multiple deformations in a long-lived, crustal-scale structure in the Mount Isa Inlier. Submitted to Tectonophysics, Dec 2007.

Austin, J. R. and Blenkinsop, T.G. (XXXX). Remote mapping of Sodic-Calcic alteration: Application to IOCG exploration in the Eastern Succession, Mount Isa Inlier. Submitted to Australian Journal of Earth Science, Feb 2008.

Austin, J. R. and Blenkinsop, T.G. (XXXX). The Cloncurry Lineament, a crustal scale control on mineralisation in the Eastern Mount Isa Inlier, Australia: Evidence from Autocorrelation and Weights of Evidence. Submitted to Mineralium Deposita, Mar 2008.

Appendices

Presentations

J.R. Austin, Digging deeper with worms: Finding Structure in Geophysics, Mount Isa Eastern Succession. Poster presented at the Predictive Mineral Discovery Cooperative Research Centre June 2004 Conference.

J.R. Austin, Crustal Structure of the Mount Isa Eastern Succession: The Cloncurry Lineament. Departmental Confirmation Seminar, September 2004.

J.R. Austin, The Cloncurry Lineament: Interpretation of a major crustal worm. At Structure, tectonics and ore mineralisation processes, Conference, Sept-Oct 2005

J.R. Austin Using regional -> deposit scale Structural insights to understand Mineralisation patterns: Mount Isa, Eastern Succession. Departmental Research Seminar October 2005

J.R. Austin, The Cloncurry Lineament: Data collection and work in progress. I7 Project meeting, Brisbane, 24-25 October, 2005

Conferences

Predictive Mineral Discovery Cooperative Research Centre, June 2004 Conference, Barossa Valley.

Australian Society of Exploration Geophysics, August 2004 Conference, Sydney.

Structure Tectonics and Ore Mineralisation Processes, September-October 2005, Townsville, Australia

Predictive Mineral Discovery Cooperative Research Centre, April 2006 Conference, Perth, WA.

SEG, Wealth creation in the Minerals Industry, Annual Conference, May 2006, Keystone, Colorado, USA

Australian Earth Science Convention, July 2006, Melbourne, Victoria

Appendices

Fieldtrips

Pmd*CRC Mount Isa, Eastern Succession fieldtrip, July 2004

STOMP, NE Queensland fieldtrip, September 2005

SEG, Carlin trend, Utah/Nevada, USA, May 2006

Short Courses and Workshops

“Kickstart your Thesis”, Generic Skills Course, JCU

“An introduction to worms” workshop, Geoscience Australia.

“Advanced techniques in Mining and Mineral exploration”, Masters Module, JCU

“Spatial Modelling using GIS for Mineral Exploration” ”, Masters Module, JCU

“Geochronology” short course, pmd Education and training.

“3D modelling workshop” Geoscience Australia

“Young Scientists Workshop” leadership and team work course, Adventure West